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DEVELOPMENT OF TERMINATION AND UTILIZATION CONCEPTS FOR FLAT CONDUCTOR CABLES

Volume II

Utilization of Small-Gage-Wire Round Conductor Cables

D6-40711-2

July 1972

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THE BOEING COMPANY

Seattle, Washington 98124

for

Manned Spacecraft Center, Houston

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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FOREWORD

This is volume II of a three-volume report prepared under contract NAS9-12062, "Development of Termination and Utilization Concepts for Flat Conductor Cables."

The other two volumes are:

Volume I (D6-40711-1)	Development of Low-Profile Flat Conductor Cable Connecting Device and Permanent Splice
Volume III (D6-40711-3)	Cost Study Comparison, Flat Versus Round Conductor Cable

CONTENTS

DEVELOPMENT OF TERMINATION AND UTILIZATION CONCEPTS FOR FLAT CONDUCTOR CABLES

Volume II

Utilization of Small-Gage-Wire Round Conductor Cables

The Boeing Company
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SUMMARY

The program phase reported herein was directed toward the practical use of small-gage round wire for electrical wiring in manned air and space vehicle environments. The program consisted of a study of wire constructions and candidate wire harness concepts, fabrication of small-gage wire (SGW) harnesses, and verification and evaluation of promising configurations by laboratory test.

Two AWG 30 wire constructions were selected for harness fabrication. One was silver-plated high-strength copper alloy 135, 7 by 38 stranding, with 5 mils of Kapton/FEP insulation. The other was 6 by 38 silver-plated high-strength copper alloy 135 and 1 by 38 stainless steel 304, with 6 mils of cross-linked polyalkene insulation (MIL-W-81044/19).

Laboratory tests show that SGW harnesses with tensile members will provide the required axial loading (designer's choice) while being lighter, smaller in diameter, more flexible, and more abrasion resistant than conventional AWG 24 wire bundles.

SGW harnesses with tensile load-bearing members and suitable backshell hardware, modified connector contacts, and braided jackets are considered the lightest configuration practical, both to fabricate and maintain.

INTRODUCTION

Present wiring philosophy dictates that each wire in an electrical wire bundle, in addition to its electrical requirements, be adequately designed for environmental stresses which only the outer wires encounter. Weight and space reduction can be realized by using smaller gage wire with thinner wall insulation adequate to comply with the electrical requirements. Protection from external environmental stresses can then be provided by use of multiconductor cabling techniques.

This study is directed toward application of small-gage wire (SGW) in a space vehicle having an approximate length of 120 ft, a diameter of 12 ft, a pressurized area for 8 to 10 people, and a cargo volume of 60-ft length by 12-ft diameter. The unpressurized area wiring may experience temperature excursions up to 600° F and above for short durations (10 minutes). This study is confined to the least hostile environments of the pressurized areas within the vehicle. An initial application of SGW technology could be considered for the Space Shuttle program.

Because of its tensile strength limitations, SGW has not been used extensively in aerospace vehicles for general wiring. In the Lunar Module (LM), AWG 26 annealed copper conductors were used initially, but due to wire breakage at the terminations, the AWG 26 annealed copper wire was replaced by AWG 26 high-strength copper alloy (HSA) wire, except for the display panels which reverted to AWG 22 annealed copper wire. It is noted that AWG 26 HSA has been applied to such military programs as the B-70, B-1, and C5A. Also, limited application of AWG 26 has been made in commercial airline programs in noncritical (e.g., passenger entertainment) areas.

The testing reported in this document shows that wire for air and space vehicle electrical systems can be designed to meet the electrical parameters and that the required mechanical properties can be included in the harness system.

PROGRAM OBJECTIVE

The objective of this program is to show that SGW (AWG 26, 28, and 30) can be used with integrity for vehicle system wiring. This thesis is supported and verified by the following:

- Evaluation of various SGW constructions
- Evaluation of various SGW harness designs
- Fabrication of test hardware
- Test and study program
- Delivery of SGW electrical harness assemblies to NASA Manned Spacecraft Center (MSC)

DESIGN CONSIDERATIONS

TENSILE STRENGTH

Wire

Aerospace applications of wires smaller than AWG 26 have been limited to equipment and panel installations and use of high-strength copper alloy (HSA) material. HSA offers a substantial tensile advantage over annealed copper, with an acceptable reduction of conductivity.

On the premise that the circuits using AWG 24 or 26 wires have a low current requirement, conductivity is not of major consequence and accordingly reduced conductivity becomes acceptable.

To evaluate the mechanical properties of SGW, various constructions of HSA and stainless steel stranding were considered, i.e., AWG 30 with a core of 1 strand of AWG 38 stainless steel surrounded by 6 strands of HSA and AWG 30 with 16 HSA copper conductors, one strand of stainless steel as the core, and another two stainless steel strands placed diametrically opposite in the inner layer.

Table 1 compares various wire constructions, wire sizes, and tensile strengths.

TABLE 1.–WIRE COMPARISON

Wire gage, AWG		22	24	26		28		30		
Cross-sectional area, sq in.		0.000503	0.000317	0.000199		0.000125		0.000078		
Construction	Wires x AWG	19x34	19x36	19x38	19x38	7x36	19x40	7x38	19x42	19x42
	Wires/material[a]	19/Cu	19/HSA	19/HSA	16/HSA 3/SS	6/HSA 1/SS	16/HSA 3/SS	6/HSA 1/SS	16/HSA 3/SS	12/HSA 7/SS
Break strength, lb		23.32	20.5	13.15	15.35	8.7	9.92	5.59	6.04	7.20
Conductivity, % of AWG 24		17 5	100	62.6	52.71	33.77	33.07	21.27	20.82	15.58
Weight, lb/1000 ft		2.37	1.5	0.952	0.952	0.546	0.577	0.350	0.379	0.379

[a]Cu = Annealed copper, based on 36 000 psi
HSA = High-strength alloy, based on 55 000 psi
SS = Stainless steel, based on 115 000 psi

Wire Constructions

Seven different types of wire construction were tested and compared for tensile strength, abrasion, flexure, and weight to determine the optimum wire design. Each of the wire constructions is defined in table 2.

TABLE 2.—SMALL-GAGE WIRE CONSTRUCTION

Symbol	AWG	Conductor	Insulation	Applicable military specification
A	30	7x38 silver-plated high-strength copper alloy 135	6-mil crosslinked polyalkene	MIL-W-81044/13
B	30	6x38 silver-plated high-strength copper alloy 135 and 1x38 stainless steel 304	6-mil crosslinked polyalkene	—
C	30	7x38 silver-plated high-strength copper alloy 135	5-mil polyimide—616 tape (1/2-mil FEP, 1-mil Kapton, 1/2-mil FEP, 66% overlap)	—
D	30	7x38 silver-plated high-strength copper alloy 135	10-mil type-E Teflon (ribbon)	MIL-W-16878/4A
E	30	7x38 silver-plated high-strength copper alloy 135	5-mil type ET Teflon (ribbon)	MIL-W-16878/6A
F	25	Flat conductor unplated copper	4-mil-wall FEP + H-film each side	MIL-W-55543
G	24	19x36 silver-plated high-strength copper alloy	10-mil crosslinked polyalkene	MIL-W-81044/19

Wire Bundles

Accepted design practice for wire bundles allows a minimum bundle size of three AWG 24 HSA wires. Therefore, a bundle strength equal to the strength of three AWG 24 HSA wires is considered acceptable. The values shown in table 3 were established by tests to show what can be expected in wiring practice.

TABLE 3.—BARE AND INSULATED WIRE TENSILE STRENGTHS

Wire	Break strength, lb			
	Bare conductors		Insulated conductors	
	Single	Three	Single	Three
AWG 24 HSA	23.7	71.1	37.5	112.5

Harness Systems

SGW harnesses should equal or exceed the minimum tensile strength required for conventional wire bundles.

Tensile Members

To achieve the tensile strength design requirement for wire harnesses, the following must be considered:

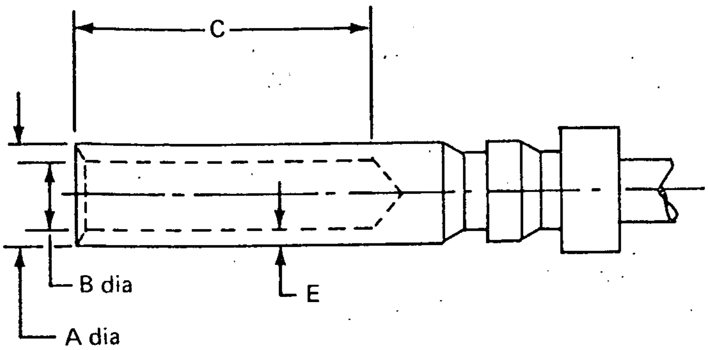
- The minimum number of wires which will collectively provide the required harness strength, or
- A tensile load-bearing member of sufficient strength installed as an integral part of the wire harness.

MODIFIED CONNECTOR CONTACTS

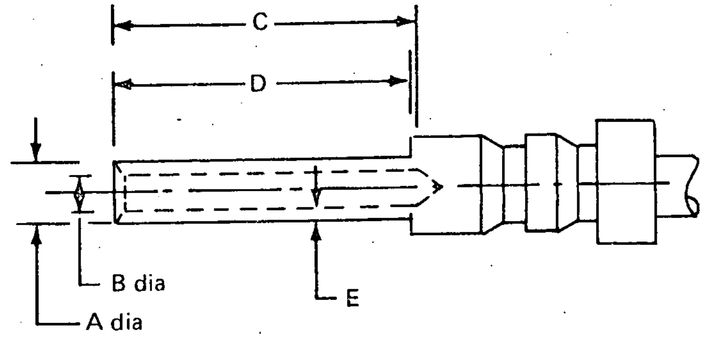
In the application of SGW it is considered advantageous to have a strain relief sleeve that will provide support to the terminated wire. To achieve this it was necessary to obtain 22D size contacts with crimp barrels unbored so that modifications could be made to accept the shrinkable sleeve without interfering with the contact operation or processing.

The details and comparison of the MS27493 22D standard contact and the modified contact are shown in figure 1. Note particularly the smaller wire barrel to better accept AWG 30 wire, the reduced crimp barrel diameter so that crimp evaluation becomes necessary, and the capability of placing a sleeve over the crimp barrel without interfering with the contact removal tool, i.e., the overall diameter over the sleeve is not greater than the nominal crimp barrel diameter (0.048/0.046 in.) of the standard 22D contact. This contact was modified to demonstrate feasibility and a limited number of crimp tests were performed.

The sleeve increases the wire diameter to provide an effective seal in standard connector grommets designed to accommodate wire sizes down to AWG 28. The sleeve can also serve as a means of wire identification while at the same time increasing the flexure capability of the contact-to-wire transition.



Standard Contact



Modified Contact

Contact	A dia, in.	B dia, in.	C, in.	D, in.	E, wall thickness, in.	AWG 30 conductor diameter, in.
Standard	0.048 0.046	0.0355 0.335	0.157 0.141	– –	0.006	0.013
Modified	0.032 0.030	0.20 0.018	0.157 0.141	0.155 0.151	0.006	0.013

FIGURE 1.–CONTACT COMPARISON–STANDARD VS MODIFIED

FLEXURE

Individual wires and wire bundles are subjected to flexure forces during fabrication, termination, installation, rework, and maintenance. Field service data indicate that most wire breakage occurs locally near the end of the wire run.

Flexure tests were designed to simulate "as-installed" conditions. Wire bundles were terminated in connectors and subjected to flexure stresses applied between the connector and the first structural "tiedown" to represent equipment removal and termination rework conditions.

ABRASION RESISTANCE

With SGW and thin-wall insulation, jacketing is a requirement. The type of installation will determine the jacketing abrasion characteristics. Jacketing techniques are required to satisfy a level of abrasion resistance equal to or greater than that of MIL-W-81044/19 conventional AWG 24 wire.

FABRICATION

Existing materials and hardware should be used for harness fabrication where possible. Items specially fabricated should be limited to those required to make SGW harness applications feasible.

DESIGN GOALS

The following design goals were established to set "accept-reject" limits for use in the test and evaluation phases to ensure that the objectives are met.

WIRE TENSILE STRENGTH

The ideal wire for this program would have a minimum tensile strength equal to the contact retention force. The contact retention force per MIL-C-38999 is 10 lb minimum for a size 22D contact.

SGW HARNESS TENSILE BREAK STRENGTH

The tensile break strength design goal for SGW harnesses is 110 lb minimum. This value is based on the break strength of the three-wire AWG 24 bundle per table 3.

ABRASION RESISTANCE

An SGW harness must equal or exceed the abrasion resistance of MIL-W-81044/19, AWG 24 wire.

FLEXURE

An SGW harness must withstand the number of flexes achieved by an identical conventionally designed wire bundle using MIL-W-81044/19, AWG 24 wire.

FABRICATION

Materials, parts, and processes used in SGW harnesses shall be based on current technology where possible.

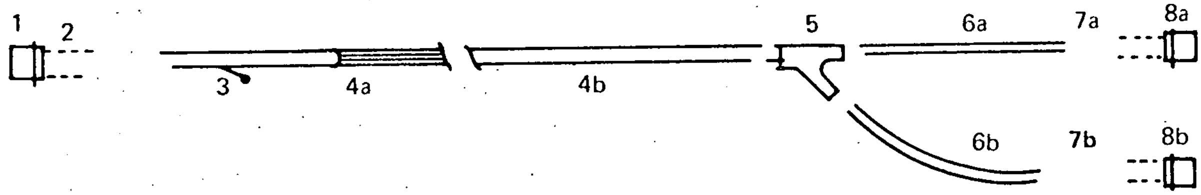
MAINTAINABILITY

SGW harness design shall be compatible with standard maintenance practices. The harnesses shall be repairable on-board the vehicle with standard tools.

B

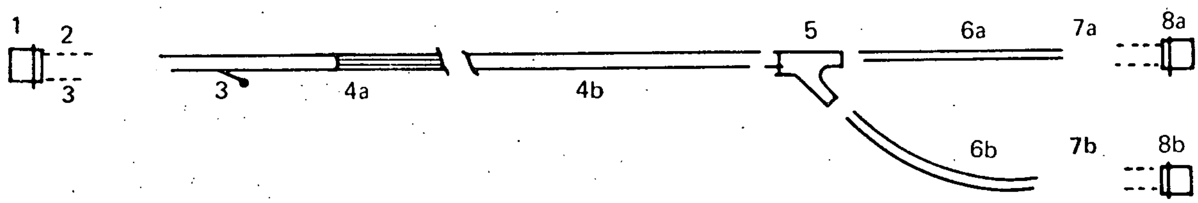
SGW HARNESS SYSTEM CONCEPTS

Figures 2, 3, 4, and 5 illustrate the various concepts considered feasible and define the hardware used. Figures 6 and 7 show actual sample assemblies. Additional detailed photos of the termination and transition areas are included (figs. 8 through 16).



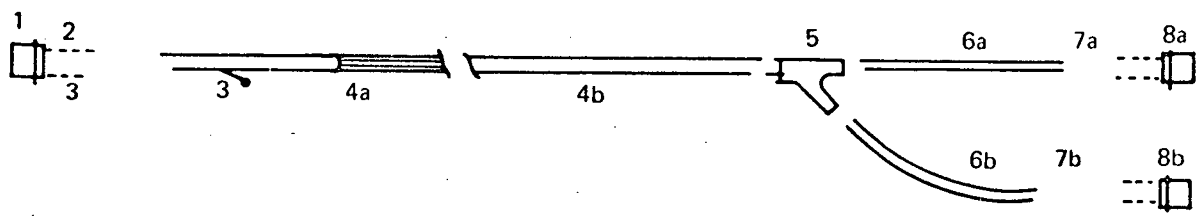
Code no.	Item	Description
1	Connector	Amphenol high-density Astro/348 connector per MIL-C-81511 (M81511 06E18-8P1) with 22D contacts (348-100-504P-02)
2	Backshell	Glenair Qwik-Ty (GTR03N18) with spacer pad (silicon—G70407-2S), Dacron wrap string over bundle, and Raychem shrinkable boot of modified polyolefin ((202A142-4)
3	Tensile member and termination	Plastic (nylon) jacketed, stainless steel (1/32 in.), 3x7 construction, 110-lb breaking strength with compression terminal fitting and detachable swivel connection to backshell hardware
4a	Main run wire bundle	55 AWG 30 wires: 6x38 silver-plated high-strength copper alloy, 1x38 stainless steel 304, 6-mil cross-linked polyalkene
		Construction (dimensions in inches, nominal): Core plus first layer (17 wires)—1.77 left hand lay, 0.120 OD; Second layer (16 wires)—2.05 right hand lay, 0.168 OD; Third layer (22 wires)—2.82 left hand lay, 0.216 OD; Filament binders applied at each layer as required.
4b	Main run jacketing	Nomex braid (32 carriers, four ends up, 1200 denier, 600-filament fiber)
5	Junction	Nomex braid (jacket as in 4b)
6a	Branch, upper	33 wires (core plus first and second layers of main run bundle) with tensile member, jacketed with Nomex braid
6b	Branch, lower	22 wires (third layer of main run bundle) with braid-to-convoluted-tubing adaptor plus structure tiedown.
		Extra-thin-wall, double-convoluted, 10-mil, FEP flexible tubing
7a	Backshell, upper	Modified backshell cable clamp for tensile member termination
7b	Backshell, lower	Icore, series 552 convoluted-tubing-to-connector fitting
8a	Connector, upper	Bendix high-density (JT06RE-14-35P(SR)) with 22D contacts per MIL-C-38999
8b	Connector, lower	Bendix high-density (JT06RE-12-35P(SR)) with 22D contacts per MIL-C-38999

FIGURE 2.—HARNESS ASSEMBLY 1



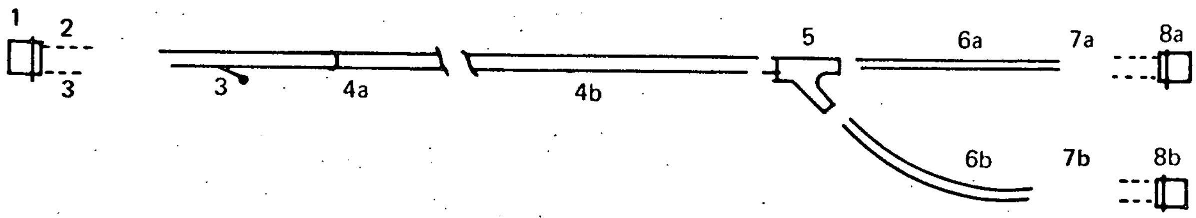
Code no.	Item	Description
1	Connector	Same as harness assembly 1
2	Backshell	Same as harness assembly 1
3	Tensile member and termination	Same as harness assembly 1
4a	Wire bundle	55 AWG 30 wires: 7x38 silver-plated high-strength copper alloy 135, 5 mils polyimide 616 tape (1/2 mil FEP, 1 mil Kapton, 1/2 mil FEP, 66% overlap) Construction: Same as harness assembly 1 except 1/4-in. teflon tape used as binder
4b	Jacketing material	Same as harness assembly 1
5	Junction	Same as harness assembly 1
6a	Branch, upper	Same as harness assembly 1
6b	Branch, lower	Same as harness assembly 1
7a	Backshell, upper	Same as harness assembly 1
7b	Backshell, lower	Same as harness assembly 1
8a	Connector, upper	Same as harness assembly 1
8b	Connector, lower	Same as harness assembly 1

FIGURE 3.—HARNESS ASSEMBLY 2



Code no.	Item	Description
1	Connector	Same as harness assembly 1
2	Backshell	Bendix modified backshell hardware and three-legged plastic molded cone, Dacron tie string.
3	Tensile member and termination	Plastic (nylon) jacketed, stainless steel (3/64 in.), 7x7 construction, 270-lb breaking strength with detachable compression terminal and structure tiedown; tensile member on top branch run only
4a	Wire bundle	Same as harness assembly 2
4b	Jacketing material	Thermofit Kynar heat shrinkable tubing, 3/8 in. expanded inside diameter, 12-mil recovered wall thickness
5	Junction	Raychem molded Y-transition for cable breakout (342A215); 382A023 better choice—smaller, lighter
6a	Branch, upper	33 wires with tensile member jacketed with heat-shrinkable tubing; tensile member breakout for structure tiedown.
6b	Branch, lower	22 wires with 10-mil FEP convoluted tubing
7a	Backshell, upper	Glenair Qwick-Ty (GTR04-14L) with silicone spacer pad
7b	Backshell, lower	Icore, series 552 convoluted-tubing-to-connector fitting
8a	Connector, upper	Same as harness assembly 1
8b	Connector, lower	Same as harness assembly 1, except with modified contact barrel to accept shrinkable sleeve

FIGURE 4.—HARNESS ASSEMBLY 3



Code no.	Item	Description
1	Connector	Same as harness assembly 1
2	Backshell	Same as harness assembly 1
3	Tensile member and termination	None
4a	Wire bundle	Same as harness assembly 3
4b	Jacketing material	Same as harness assembly 3
5	Junction	Same as harness assembly 3
6a	Branch, upper	Same as harness assembly 3, but with no tensile member.
6b	Branch, lower	Same as harness assembly 3
7a	Backshell, upper	Same as harness assembly 3
7b	Backshell, lower	Same as harness assembly 3
8a	Connector, upper	Same as harness assembly 3
8b	Connector, lower	Same as harness assembly 3

FIGURE 5.—HARNESS ASSEMBLY 4

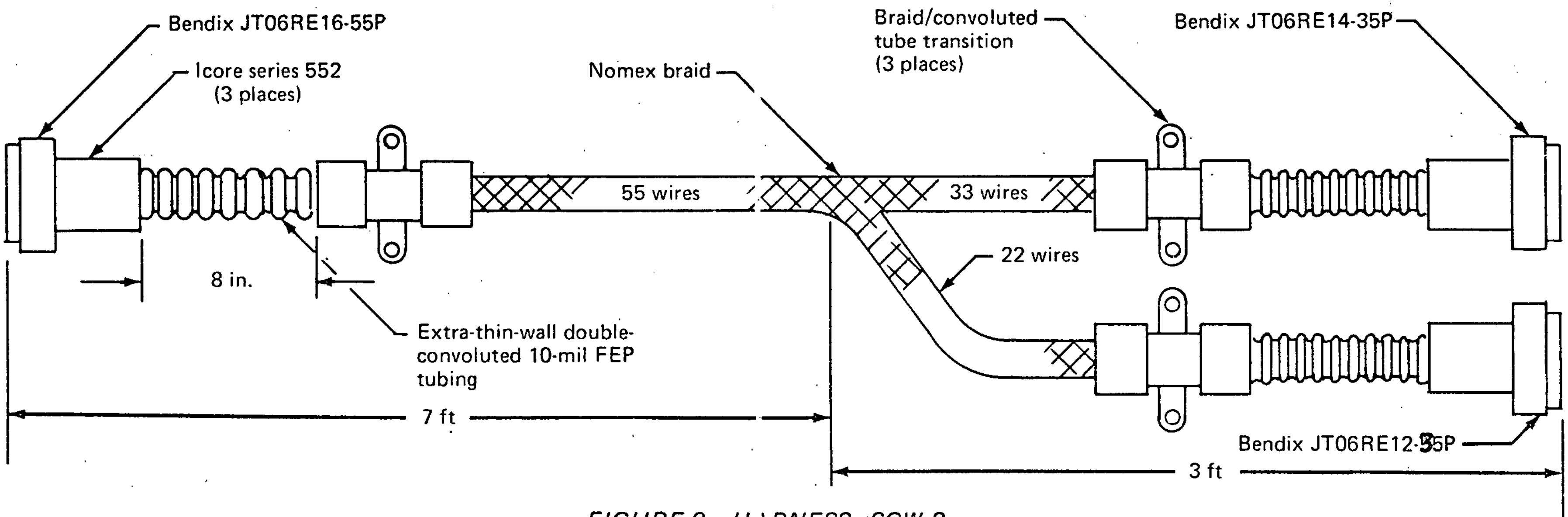


FIGURE 9.—HARNESS—SGW-2

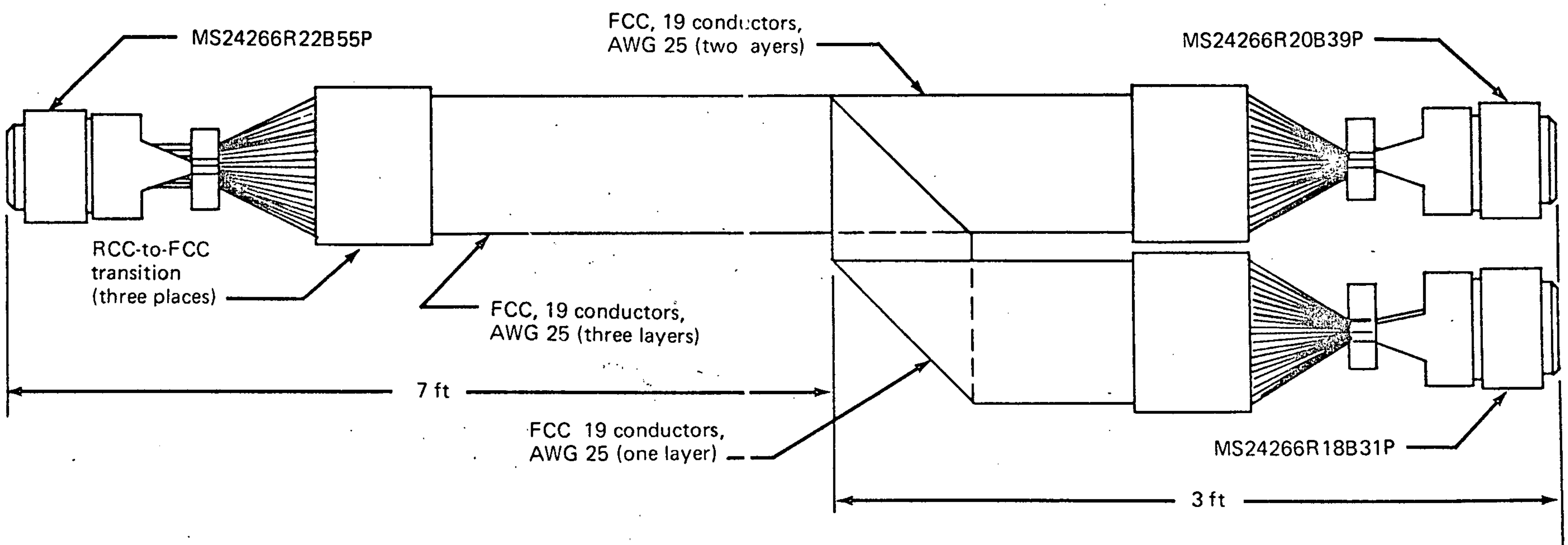


FIGURE 10.—HARNESS FCC-TS-1

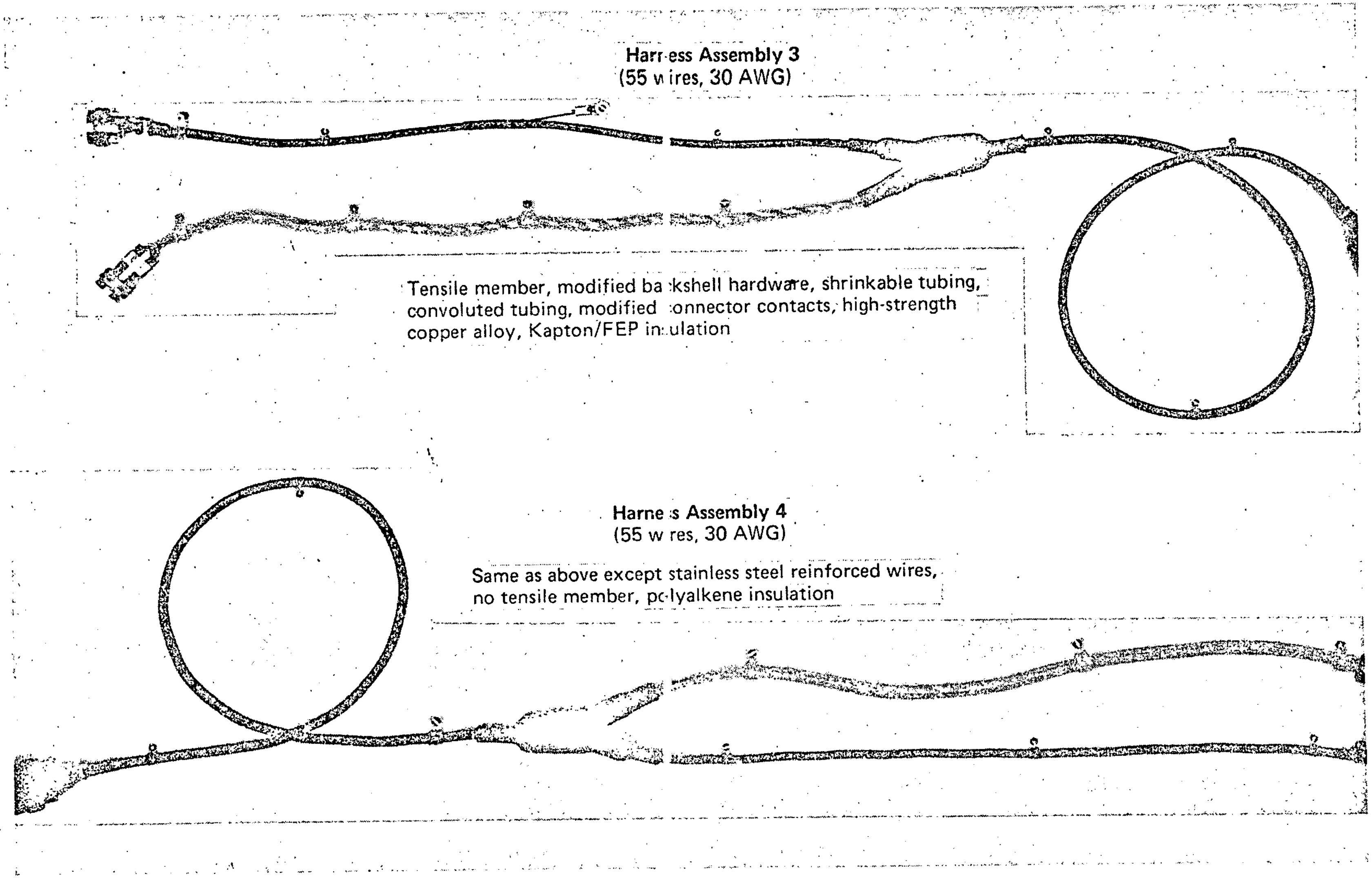


FIGURE 7.—SGW HARNESS ASSEMBLIES 3 AND 4

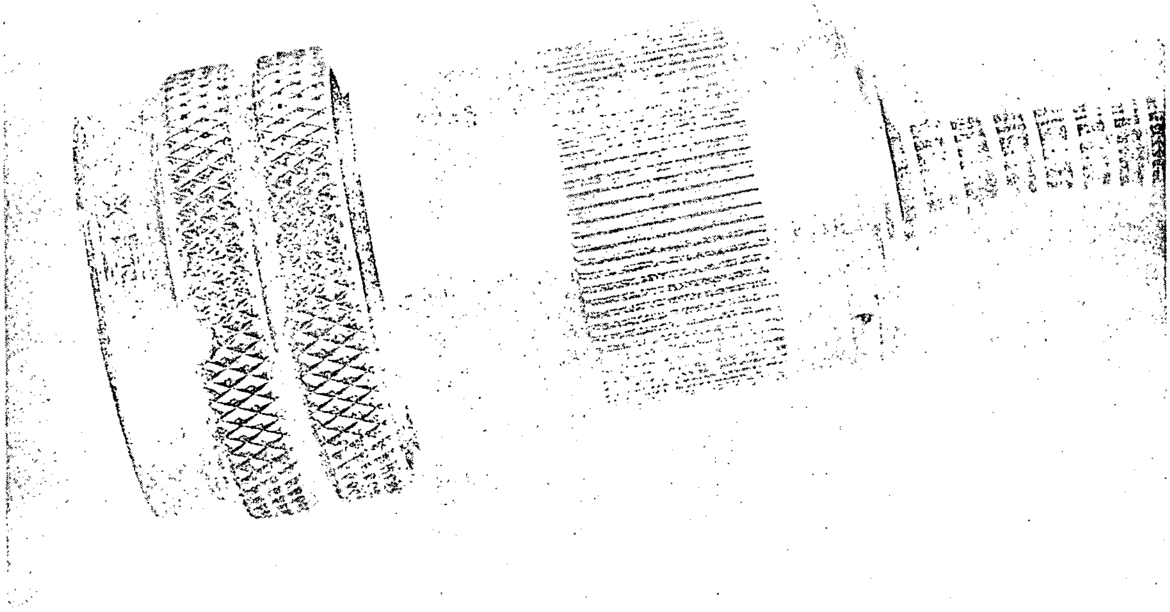


FIGURE 8.—CONVOLUTED TUBING CONNECTOR BACKSHELL ADAPTOR—COUPLED

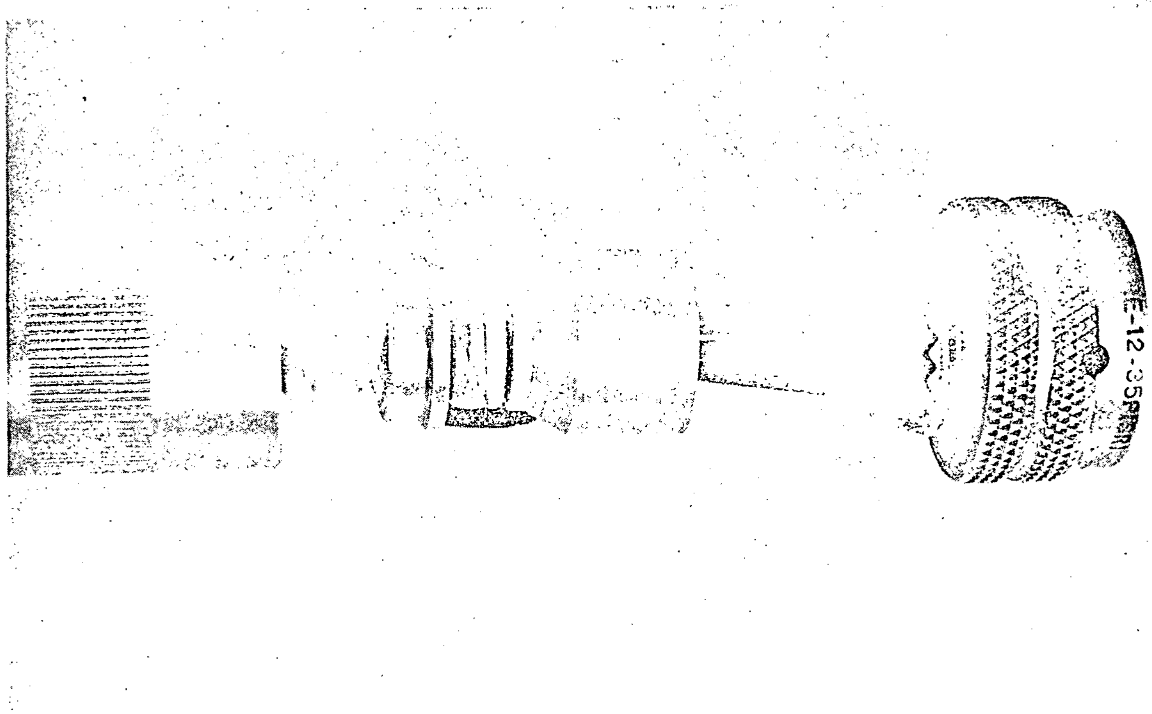


FIGURE 9.—CONVOLUTED TUBING CONNECTOR BACKSHELL ADAPTOR—UNCOUPLED

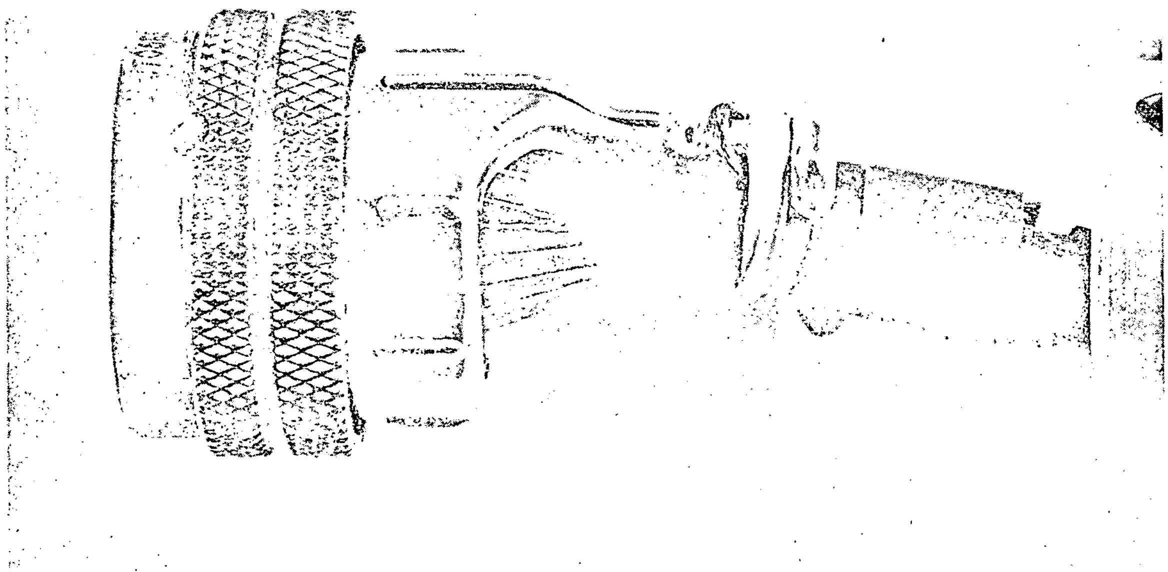


FIGURE 10.–CONNECTOR BACKSHELL INCLUDING TENSILE MEMBER TERMINATION

FIGURE 11.–CONNECTOR BACKSHELL WITH TENSILE MEMBER AND SHRINKABLE BOOT

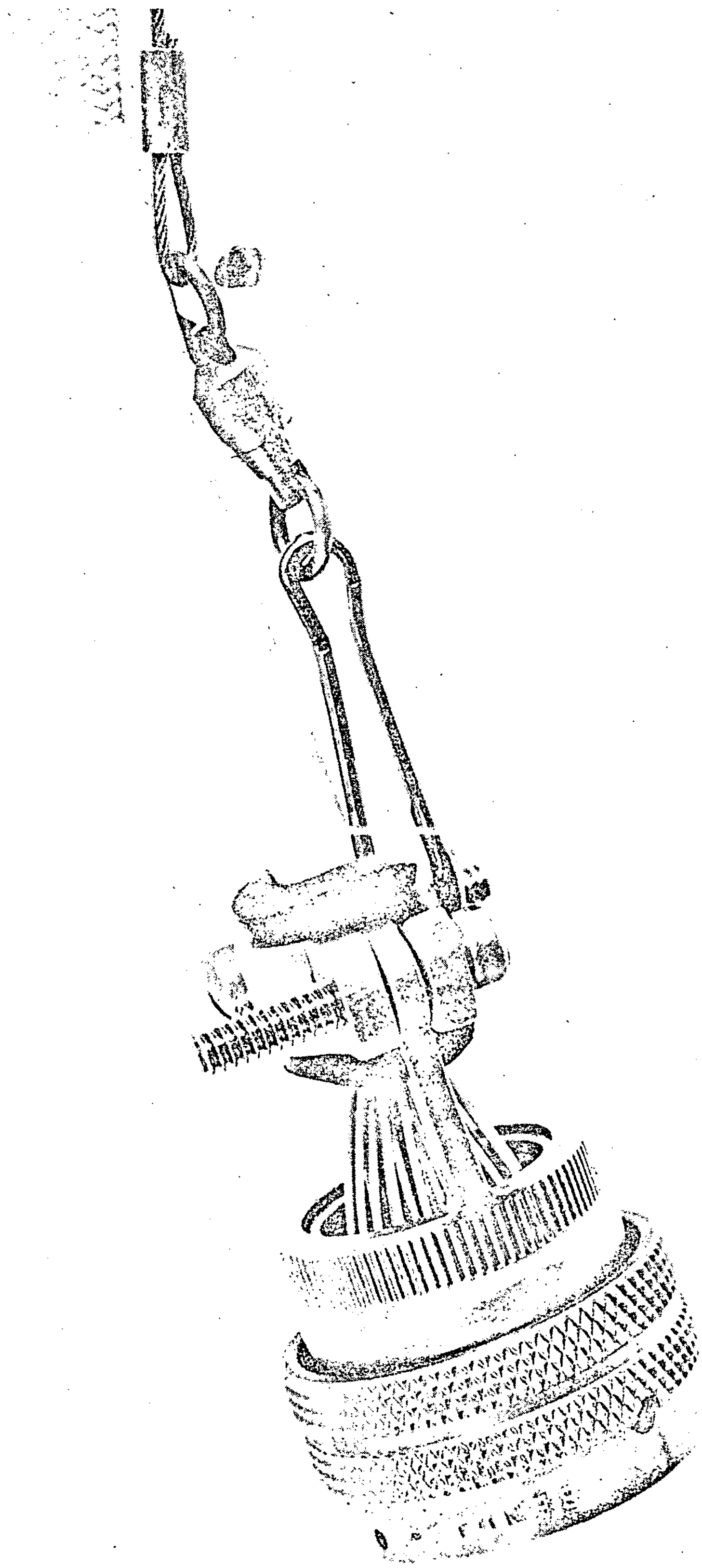


FIGURE 12.—CONNECTOR BACKSHELL, TENSILE MEMBER WITH SWIVEL HOOK, AND CONVENTIONAL BUNDLE CLAMP

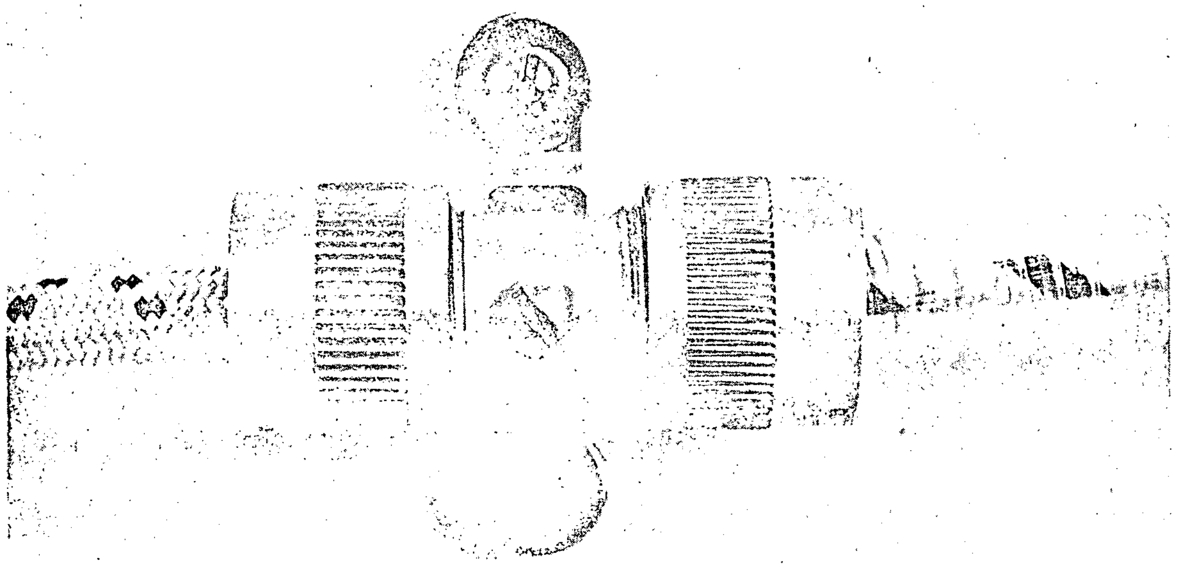


FIGURE 13.—BRAID/CONVOLUTED TUBING TRANSITION AND STRUCTURAL TIEDOWN—COUPLED

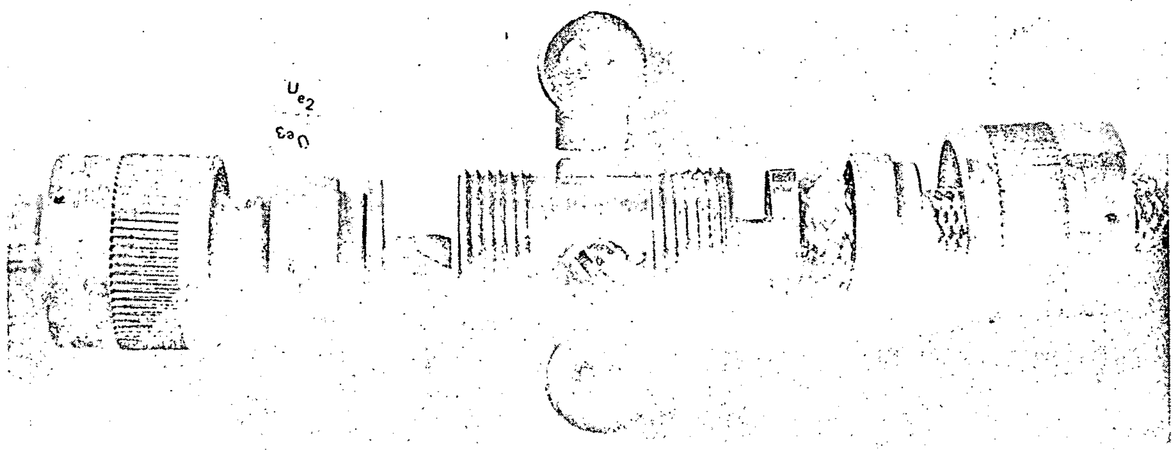


FIGURE 14.—BRAID/CONVOLUTED TUBING TRANSITION—UNCOUPLED

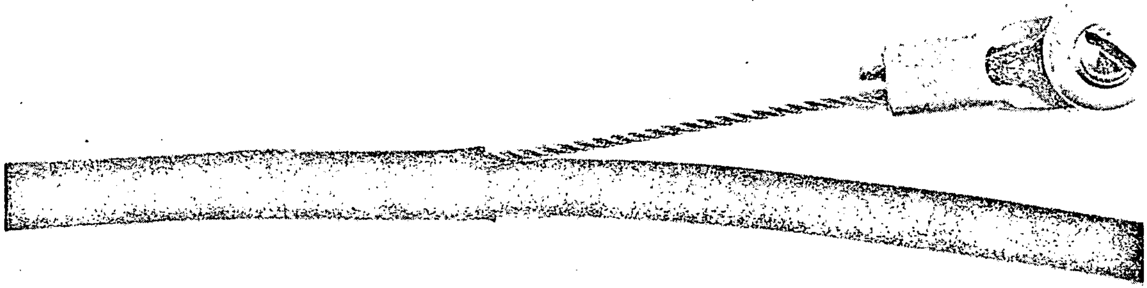


FIGURE 15.—HARNESS TENSILE MEMBER WITH STRUCTURE TIEDOWN

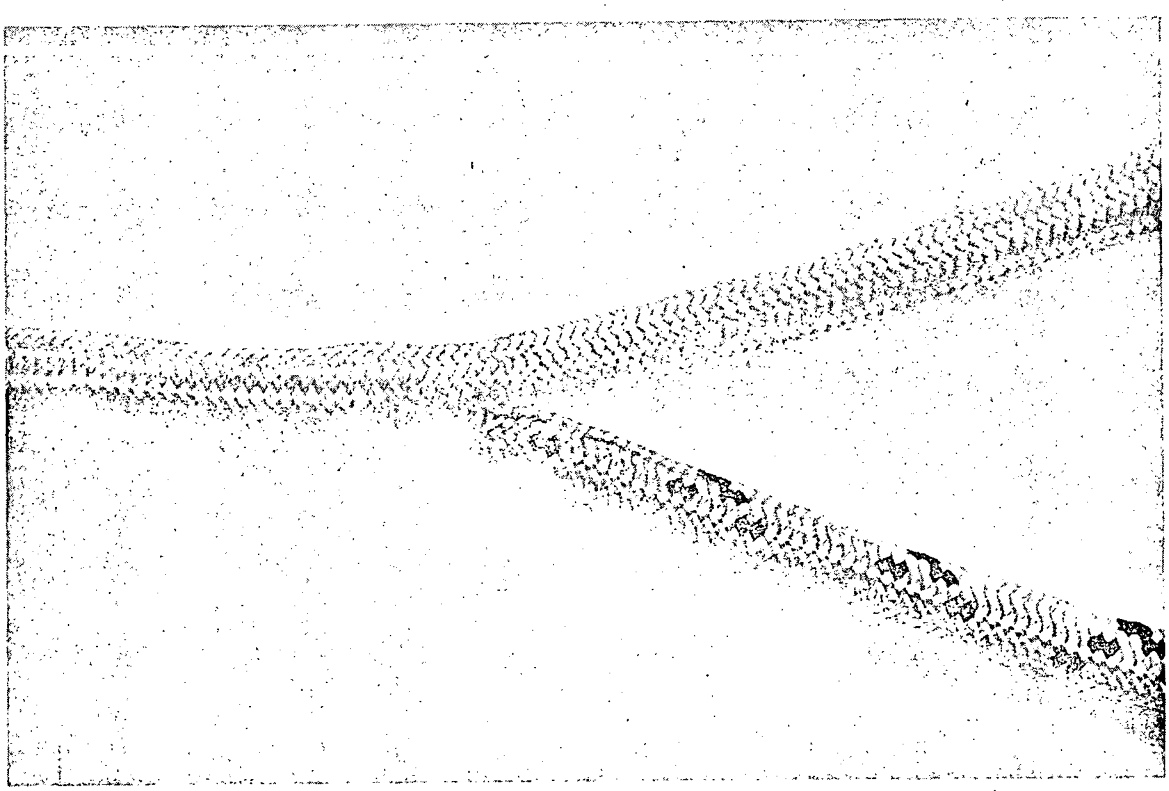


FIGURE 16.—BRAIDED HARNESS BREAKOUT

TEST PROGRAM AND DATA

The objective of the testing program was to obtain sufficient data to evaluate the ability of the small-gage wire (SGW) to function and survive in the natural and induced environment encountered in the production and service life of air and space vehicles. In this respect the overriding concern was directed to the physical and mechanical properties of SGW.

A test plan containing the test procedures and requirements is provided in the appendix. The types and severity of the tests used were evolved from the design goals established for use of SGW. Where possible, existing military specification and test methods were used as a guide. The evaluation testing was conducted on a comparative basis and divided into three categories of testing in the following sequence:

- Wire evaluation tests
- Bundle evaluation tests
- System evaluation tests

The baseline on each of the evaluations was AWG 24 wire per MIL W 81044/19 of high-strength copper alloy 135.

WIRE TESTS AND DATA

Fifteen wire samples 20 in. long, of each of the wire constructions listed in table 2, were included in the following tests.

Tensile

The break strength of each wire type was determined with and without insulation. Strands of stainless steel and high-strength copper alloy (HSA) were tested and their break strength determined. Table 4 gives the tensile test results for each wire type. The Instron tensile machine was calibrated and used for this test. Special jaws were used for equal distribution of axial load and clamping of the wire without causing damage to insulation and premature failure. Figure 17 shows the Instron tensile machine and the load recording equipment.

TABLE 4.–WIRE BREAK STRENGTH TEST DATA[a]

Symbol[b]	Wire break strength, lb		Strand break strength, lb	
	Insulation	Bare	Copper	Stainless steel
A[c]	9.2	5.6	0.72	–
B	9.3	5.6	0.75	1.8
C[c]	10.9	5.7	0.78	–
D	7.2	5.6	0.66	–
E	6.7	5.8	0.75	–
F	20.5	9.5	–	–
G[d]	37.5	23.7	1.04	–

[a]Average values of five wire test segments and seven strand test segments (crosshead speed: 0.5 in. per min; chart speed: 1 in. per min).

[b]See table 2 for complete description of wire construction.

[c]Selected for system evaluation.

[d]Included for comparative purposes as a baseline.

Flexure Life

The flexure tests on individual wires were performed on the equipment shown in figure 18. This equipment includes an electrical discontinuity monitor and a counter.

Table 5 summarizes the flexure test data compiled from results of testing five samples of each wire construction. The average, maximum, and minimum values are also tabulated with test load and flex rate.

Abrasion Resistance

The scrape abrasion resistance of the various insulation materials and their thickness was determined as shown in figure 19. An automatic monitoring circuit is incorporated in this test to stop the scrape action when the blade penetrates the insulation and makes contact with bare wire.

Table 6 records the abrasion resistance data for the various wire types.

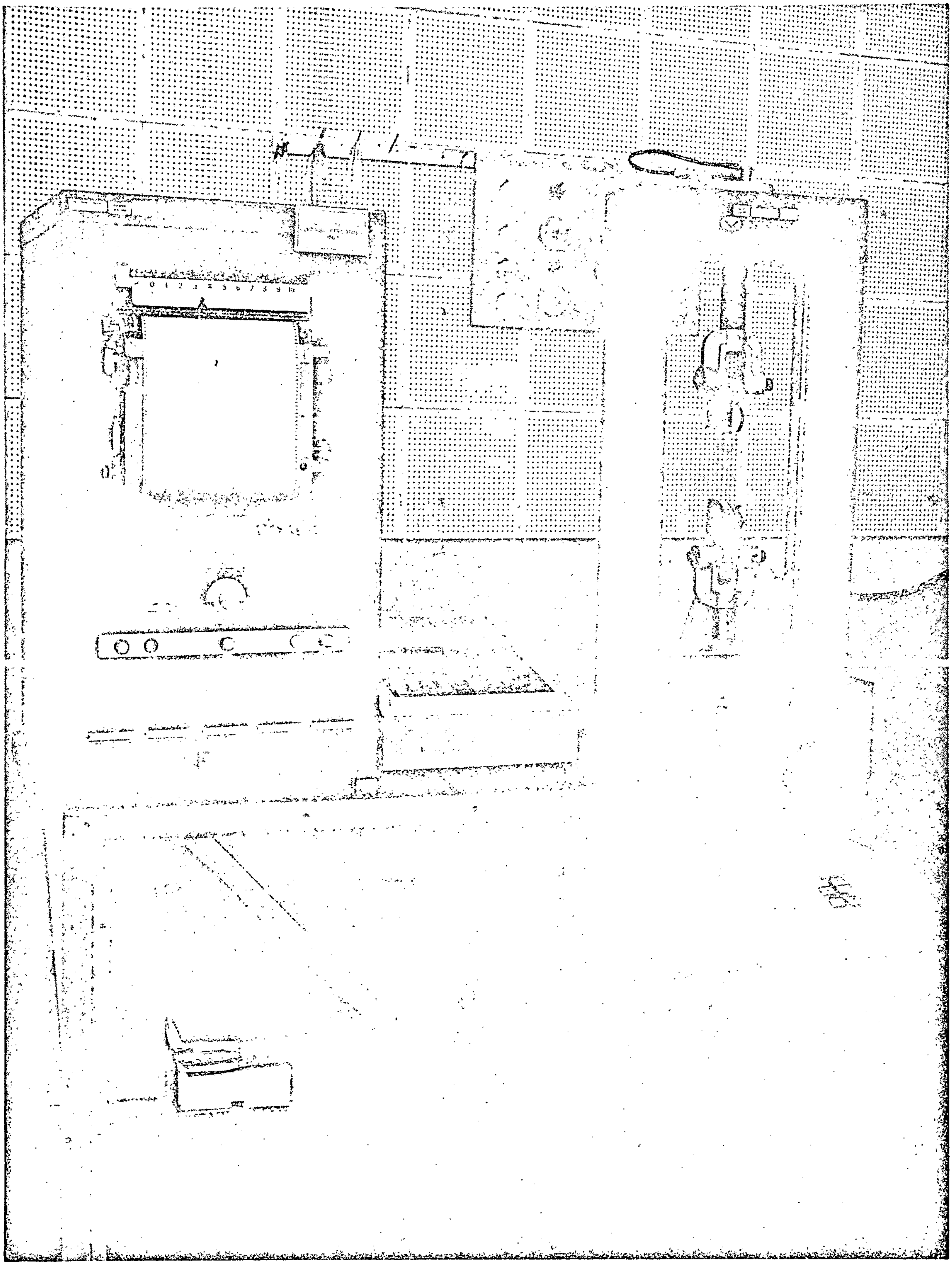


FIGURE 17.—TENSILE TEST CONFIGURATION

C

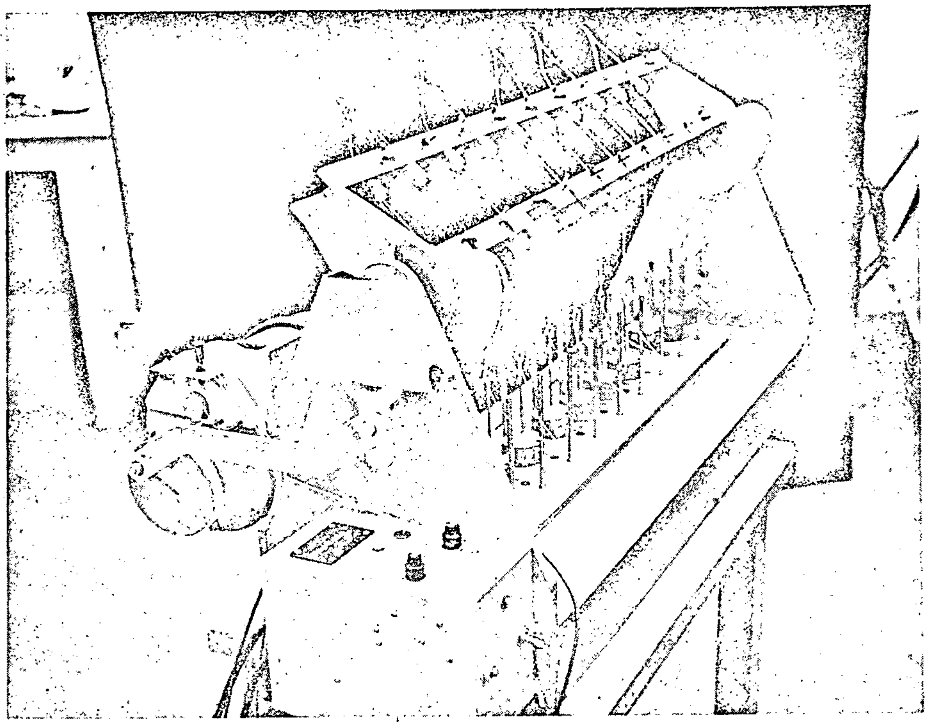


FIGURE 18.—WIRE FLEXURE TEST

TABLE 5.—WIRE FLEX TEST DATA

Symbol[a]	Flexes to failure	Mandrel radius, in.	Test load, lb	Flexes per min, ±90° arc
A	300 max 264 mean 247 min	0.128	1.2	30
B	1043 max 774 mean 680 min	0.128	1.2	30
C	350 max 203 mean 125 min	0.128	1.2	30
D	140 max 91 mean 34 min	0.128	1.2	30
E	89 max 76 mean 32 min	0.128	1.2	30
F	1006 max 701 mean 659 min	0.128	1.2	30
G	1175 max 915 mean 870 min	0.128	1.2	30

[a]See table 2 for complete description of wire construction.

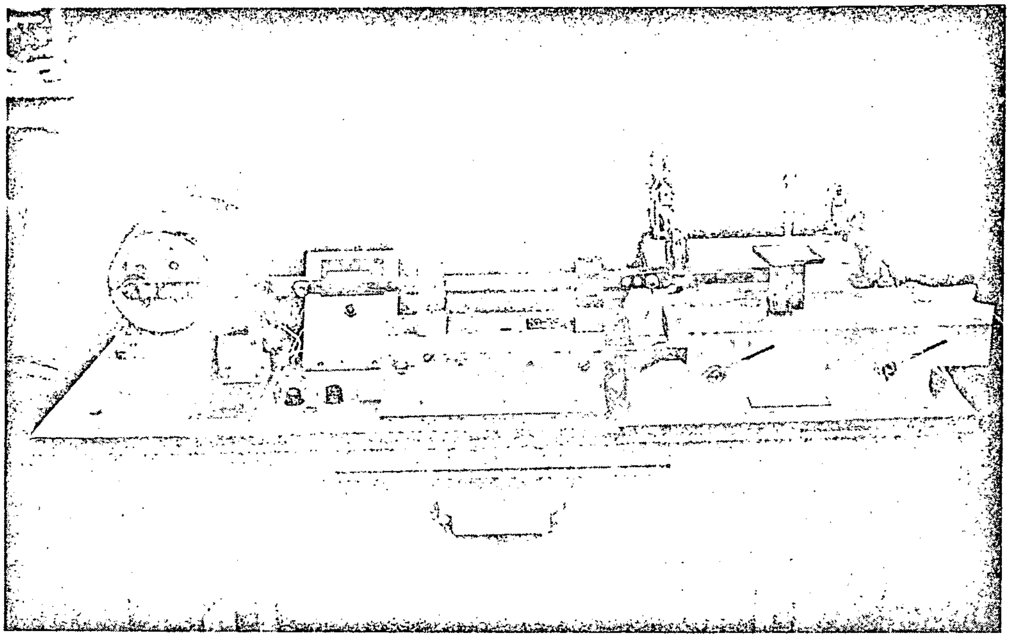


FIGURE 19.—WIRE SCRAPE ABRASION TEST

TABLE 6.—WIRE SCRAPE ABRASION RESISTANCE TEST DATA[a]

Symbol[b]	Cycles to failure — Angle of rotation of wire: 0°	90°	180°	270°
A	36	32	33	37
B	39	29	31	26
C	37	35	34	30
D	183	Individual wires cut from 19-conductor ribbon cable.		
E	10	Rotation on cut edge would give erroneous results. Only top surface of each wire tested.		
F	1911	Not applicable; flat conductor		
G	271	294	296	278

[a]Test conditions:
Speed—60 cycles per min
Blade radius—5 mil
Stroke length—2 in.
Weight on blade—1.5 lb
One cycle = two strokes

[b]See table 2 for complete description of wire construction.

Weight

Each wire construction was compared for weight on a basis of pounds per 1000 feet with respect to insulation, conductor, and finished wires. Results are shown in table 7.

TABLE 7.–WIRE WEIGHT

Symbol[a]	Weight, lb/1000 ft		
	Insulation	Bare conductor	Finished wire
A	0.200	0.347	0.547
B	0.201	0.332	0.533
C	0.187	0.350	0.537
G	0.563	1.461	2.024

[a]See table 2 for complete description of wire construction.

WIRE SELECTION

Up to this point data and test results had been collected on various wire alternatives and compared to a baseline wire of AWG 24 per MIL-W-81044/19. For further testing and evaluation of bundle and harness systems it was necessary to select the two most effective configurations by comparing the various alternatives in terms of overall systems criteria of break strength, flexure life, and scrape abrasion.

Assignment of Weighted Value to Criteria

The "weighted value" of each criterion is determined by first comparing each criterion with every other and assigning a value of 1 to whichever is judged to be the more important of any two considered and 0 to the less important. For example, since break strength is more important than flexure strength, it receives a value of 1 and flexure strength a value of 0, as shown in table 8.

To get the "weighted value" coefficient the 1's for each criterion are then summed across and divided by the total number of 1's assigned (table 8). The "weighted value" coefficient is of course a relative, not an absolute value.

TABLE 8.—ASSIGNMENT OF WEIGHTED VALUE

Criteria	Choice tally	Total	Weighting coefficient
Break strength	1 1	2	0.67
Flexure	0 1	1	0.33
Scrape abrasion	0 0	0	0.0
	Total	3	1.00

Comparison of Wire Configurations

On the basis of test data, it is now possible to compare each configuration with every other configuration on the basis of each criterion, giving the wire with, say, higher tensile strength, a value of 1 and the other wire a value of 0. The procedure is essentially the same as that used to assign weighted values. The wire configuration comparison is shown in table 9. Since there are five configurations, the total number of 1's in each tally row is divided by five to give the "choice" coefficient.

TABLE 9.—COMPARISON OF WIRE CONSTRUCTIONS

Construction[a]	Criteria	Choice tally	Total 1's	Choice coefficient
A	Break strength	0 0 1 1	2	0.40
B		1 0 1 1	3	0.60
C		1 1 1 1	4	0.80
D		0 0 0 1	1	0.20
E		0 0 0 0	0	0.00
A	Flexure	0 1 1 1	3	0.60
B		1 1 1 1	4	0.80
C		0 0 1 1	2	0.40
D		0 0 0 1	1	0.20
E		0 0 0 0	0	0.00
A	Scrape abrasion	0 0 0 1	1	0.20
B		1 1 0 1	3	0.60
C		1 0 0 1	2	0.40
D		1 1 1 1	4	0.80
E		0 0 0 0	0	0.00

[a]Supplier designations are: A, B—Raychem; C—Haveg; D, E—Gore.
Complete descriptions of each construction are found in table 2.

The final step in the wire selection process is to set up a matrix from the values obtained in tables 8 and 9. This matrix is shown in table 10. The values under each column are the product of the weighted value and the choice coefficient derived previously. As table 10 shows, the two wires chosen for further bundle and harness evaluation are B and C.

TABLE 10.—MATRIX FOR SELECTING BEST WIRE CONSTRUCTION

Criteria	Construction[a]				
	A	B	C	D	E
Break strength x 0.67	0.268	0.402	0.536	0.134	0.0
Flexure x 0.33	0.198	0.264	0.132	0.066	0.0
Scrape x 0.0	0.00	0.00	0.00	0.00	0.00
Total	0.466 3rd choice	0.666 2nd choice	0.668 1st choice	0.200	0.0

[a]See table 2 for complete description of wire construction.

WIRE STRIP TEST

The two wires selected were tested for their stripping characteristics using a Strip master wire stripper, Ideal Industries Inc., Sycamore, Ill., with a strip die, type L-5561, per MIL-W-16878, for AWG 30, 28, 26. Results are shown in table 11.

TABLE 11.—WIRE STRIPPING EVALUATION

Symbol[a]	Samples	Qualitative results
B	5	Stripped easily. No damage to conductor. No scrape of silver coating. Some fray of strands. Excellent removal of insulation. Noticeable serration left on insulation by tool-holding jaws. Under magnification, insulation ends look ragged due to tool die cutting jaws not meeting at same plane.
C	5	Same as above except there is no fray of strands. NOTE: Stripping forces required by insulation did not result in wire or strand breakage problems. SGW requires no special stripping instructions.

[a]See table 2 for complete description of wire construction.

MODIFIED CONTACT TEST

Contact Crimp

Because of the modified contact dimensions it was necessary to determine the optimum crimp tool indentor setting to produce a crimp joint with maximum tensile strength. This was required for further evaluation of wire termination and bundle flexure and tensile characteristics. To carry out this test, five sample wires were crimped at each setting within the range of the indentor setting on the crimp tool. The break strength of each group was obtained and plotted vs indentor setting, as shown in figure 20. A die closure setting of 0.016 in. is optimum.

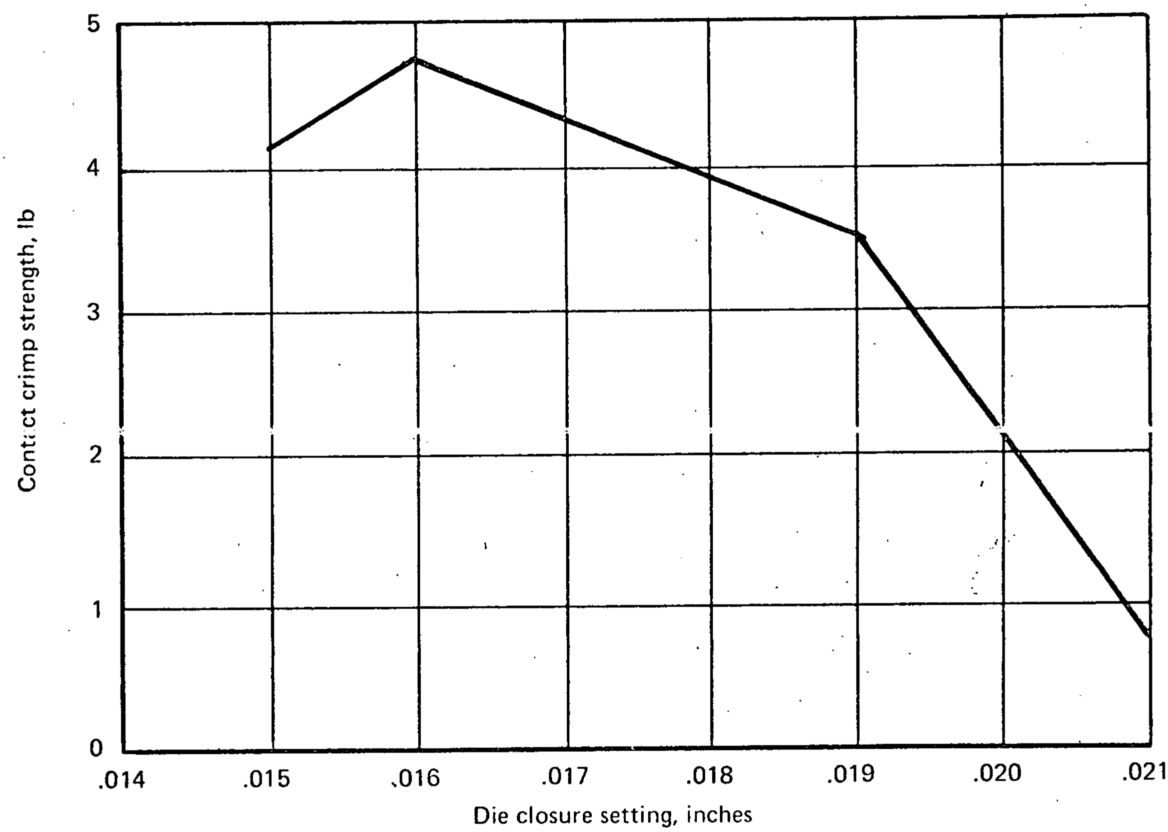


FIGURE 20.–CONTACT CRIMP CHARACTERISTICS

Contact/Wire Flexure

Having established the die closure optimum setting, the flexure life of the two selected wires was then tested with and without the shrinkable sleeving. Ten wire samples of each wire configuration were crimped at the optimum setting with modified contacts, of which five with shrinkable sleeving over the wire/contact transition were placed in a test fixture and flexed as shown in figure 21. Table 12 summarizes the test results.

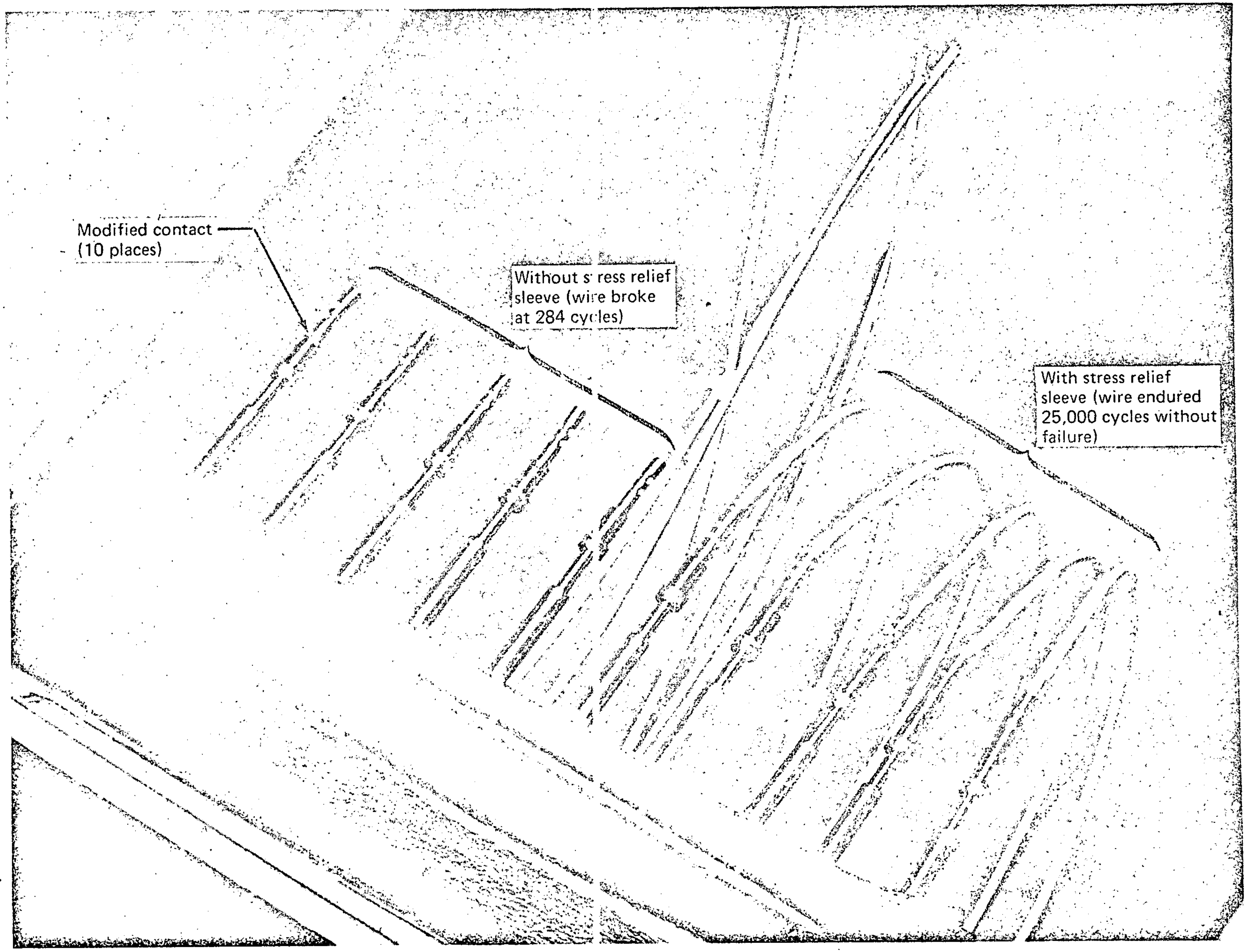


FIGURE 21.—MODIFIED CONTACT WIRE FLEXURE TEST

TABLE 12.–MODIFIED CONTACT/WIRE FLEX TEST DATA

Symbol[a]	Flex cycles	
	With strain relief sleeve[b]	Without sleeve
B	[c]25 000	562
C	[c]25 000	1756

[a]See table 2 for complete description of wire construction.
[b]1/2-in.-long sleeve of FEP-Teflon; 0.008-in. recovered wall.
[c]No failure; test stopped.

Modified Contact Crimp Strength

Ten modified contacts were crimped (at optimum setting) on one type of wire and five samples were provided with shrinkable sleeving over the contact crimp barrel/wire joint. All ten were then pulled on the tensile machine and the results recorded and averaged. Table 13 is a summary of the results.

TABLE 13.–CONTACT CRIMP STRENGTH

Die closure setting, in.	Contact	Crimp strength, lb		
		Minimum	Average	Maximum
0.023	Standard	3.72	4.55	5.8
0.016	Modified without sleeve	4.4	4.66	5.0
0.016	Modified with strain relief sleeve	4.7	4.84	[a]5.1

[a]In all cases, sleeve remained with contact.

BUNDLE TEST AND DATA

The performance of the two selected wires was compared in a bundle form without the benefit of bundle protection jacketing or strain relief. In particular, bundles were evaluated for flexure and tensile strength.

Bundle Flexure

Bundles with connector terminations were flexed to simulate stresses during handling and maintenance. This test was conducted in the configuration illustrated in figure 22. In this test, stress was applied along the wires as well as at the terminations.

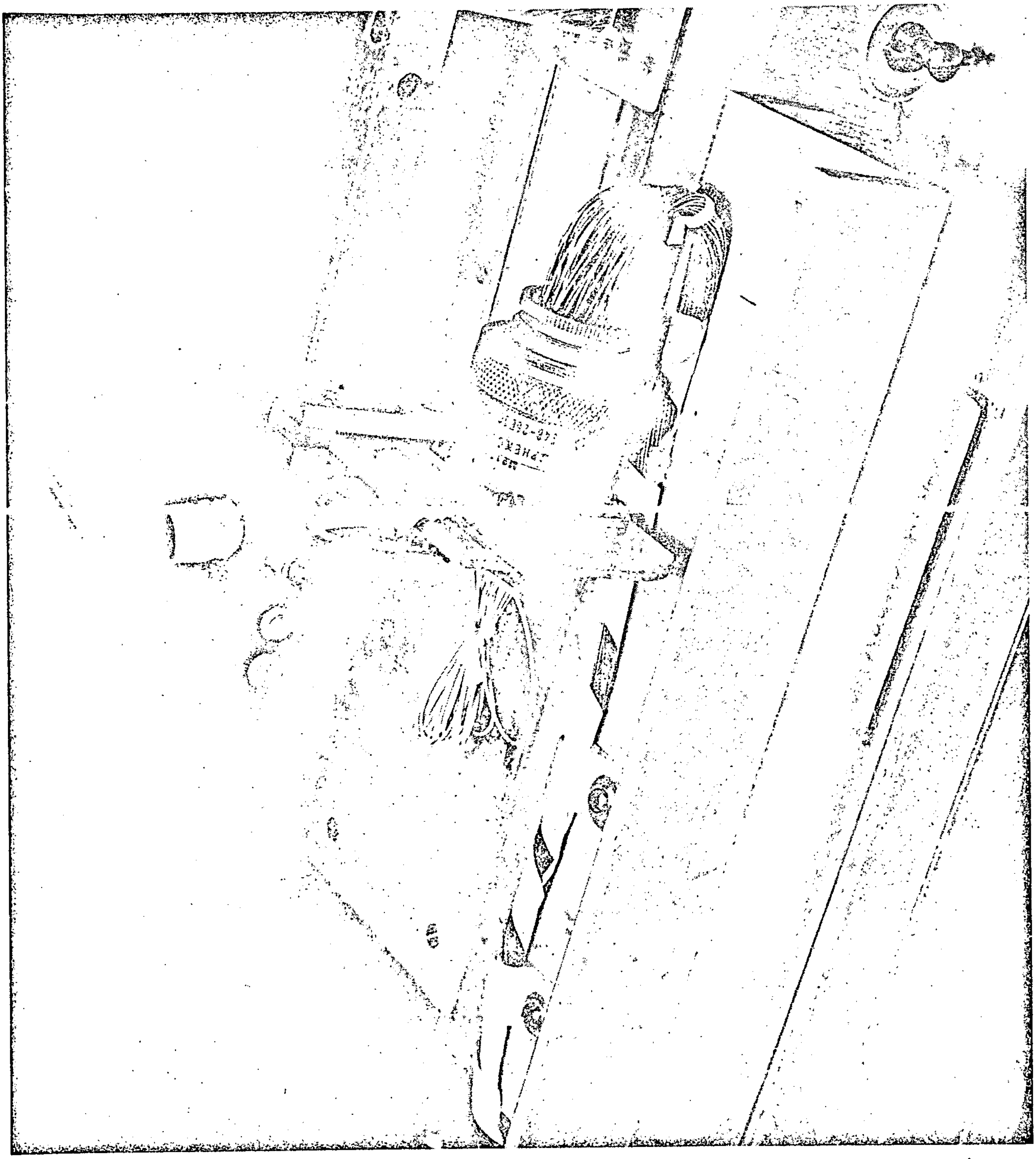


FIGURE 22.—WIRE BUNDLE FLEXURE TEST

Table 14 contains a summary of bundle flexure test results.

TABLE 14.–WIRE BUNDLE FLEX TEST DATA[a]

Symbol[b]	Wires	AWG	Contact	Flex cycles to failure[c]
B	55	30	22D	50 000
C	55	30	22D	50 000

[a]Test conditions: 60 cycles/min; no backshell hardware.

[b]See table 2 for complete description of wire construction.

[c]Test stopped; no failure. Failure of one contact or wire would have terminated test.

Bundle Break Strength

The break strength of a 55-wire bundle was determined for each of the two selected wires by pulling five bundle samples of each wire type. The Instron tensile machine was used, with a special clamping arrangement to distribute axial loading on all 55 wires to achieve load sharing. Figure 23 shows a 55-wire bundle under test with the clamping arrangement. Test data are given in table 15.

The break strength value of a 55-wire bundle obtained is indicative of "wire run" bundle strength supported at nominal intervals and away from bundle terminations.

HARNESS TEST AND DATA

Completed harness assemblies with various backshell hardware, jacketing materials, and tensile members were tested as outlined in the appendix. A complete description of four harness assemblies is included in the section "SGW Harness System Concepts," and the following tests were performed to compare these configurations and analyze their performance.

Continuity Test

Fully wired harnesses were functionally checked by continuity between contacts. All harnesses met a 100% continuity check.

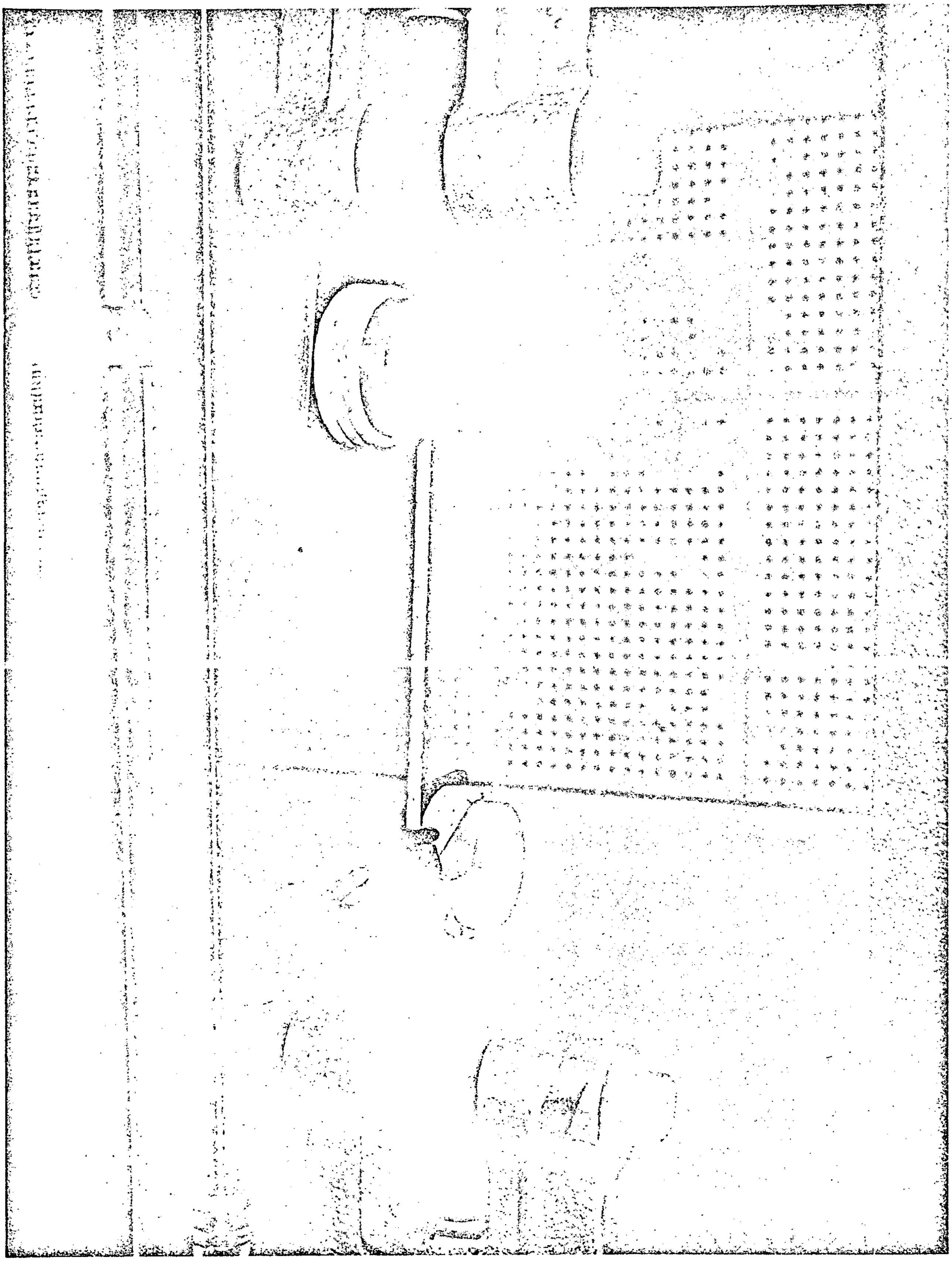


FIGURE 23.—WIRE BUNDLE TENSILE TEST

TABLE 15.–WIRE BUNDLE BREAK STRENGTH DATA

Symbol[a]	Wires	AWG	Bundle break strength, lb
B	55	30	510
C	55	30	520

[a]See table 2 for complete description of wire construction.

Assembly and Disassembly

Harness terminations with "screw-on" backshell hardware and fittings, convolute-to-braid adaptors, and braid termination hardware were assembled and disassembled 10 times. In addition, all wires crimped into contacts were stressed 10 times, under realistic work conditions, by insertion and removal from the connector. Harnesses were functional at the end of this test.

Flexure Bend Test

Since there is no flexure requirement in military specifications covering wires and wire bundles, a practical approach was taken to simulate installation and maintenance conditions. That is, wire harnesses completely assembled and fully wired were subjected to flexure and bend stress applied between the connector and the first tiedown to represent both equipment installation and removal and termination rework. A monitoring circuit was included and the flex rate was 30 cycles/min. Figure 24 shows a typical harness branch with convoluted tubing undergoing flexure testing.

Table 16 gives a summary of the configurations tested and the test results.

Harness Break Strength

For this test a connector holding fixture was incorporated into the tensile machine jaws to apply a pull on the connector. The intent of this test was to verify the impact on the total harness break strength of adding a tensile member. In addition, this test established a confidence factor and verified the integrity of the modified backshell hardware and tensile member termination techniques and hardware. To accomplish this, three bundles of 22 wires each (AWG 30, 6 by 38 HSA + 1 by 38 S/S) were terminated into a 22-contact JT connector (per MIL-C-38999) and the harness configuration completed according to table 17.

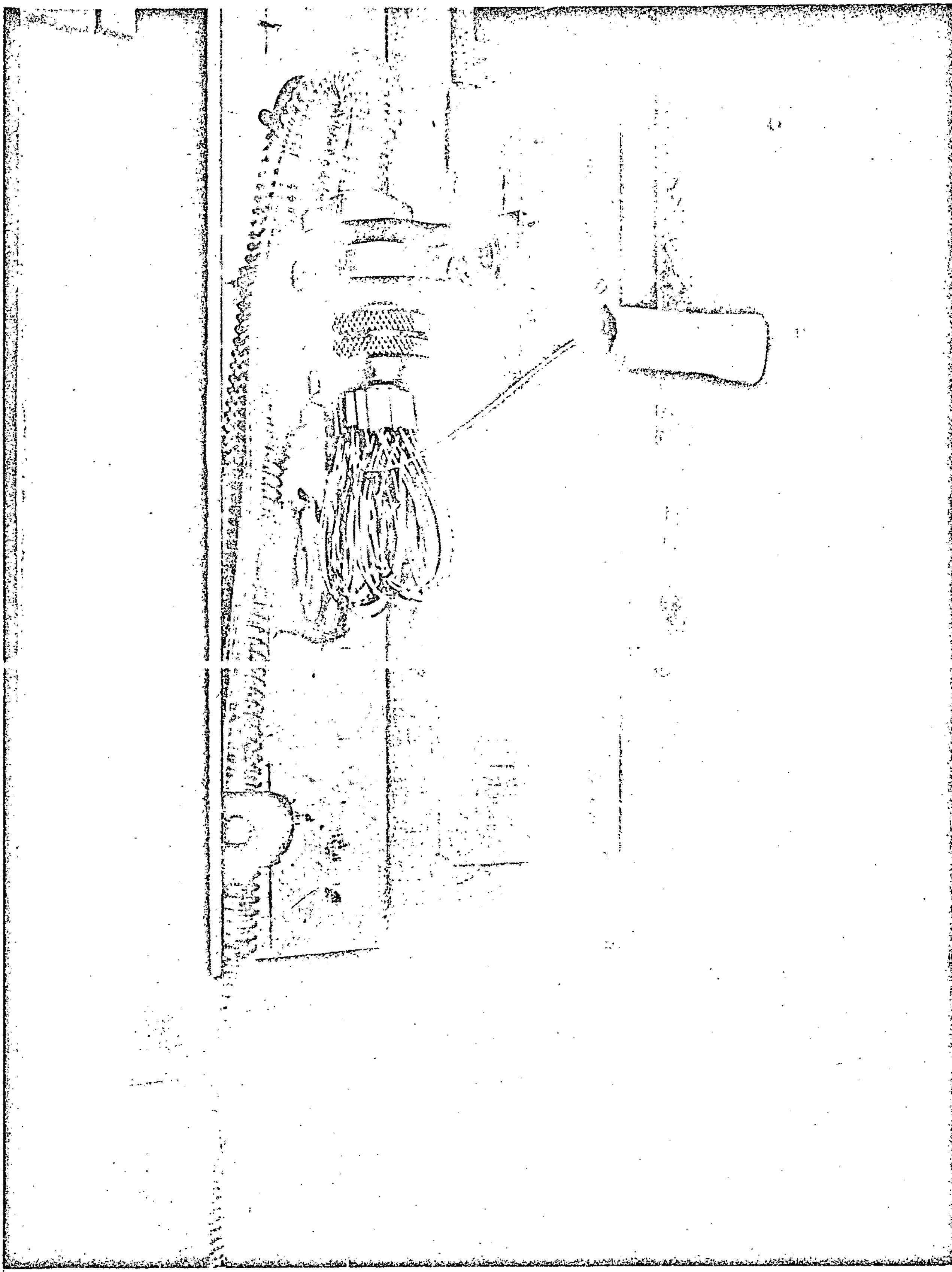


FIGURE 24.–HARNESS FLEXURE TEST

TABLE 16.–HARNESS FLEXURE BEND DATA

Harness assembly configuration	Flexure bend life, cycles[a]	Observations
55 AWG 30 wires per symbol B, table 2 terminated to MIL-C-81511 connector with convoluted tubing and backshell adaptor	92 555	Convoluted tubing developed a longitudinal split 3/4 in. long, starting 1/2 in. behind backshell; see figure 24.
Same configuration as above, except with Nomex braid and tensile member terminated to modified backshell via swivel	91 500	No electrical failure or conductor damage; all hardware intact.
Same as first configuration, except with Kynar shrinkable tubing and tensile member terminated to Qwik-Ty backshell hardware	88 000	Slight loosening of shrinkable tube sleeve used at tensile exit; all other hardware intact.

[a]Test terminated; no conductor failure.

TABLE 17.–HARNESS BREAK STRENGTH DATA[a]

Harness configuration	Break strength, lb	Failure/mode
Nomex braid over 22 AWG 30 wires terminated to J1 connector (22 pins, standard backshell)	84.5	Wires broke or pulled out at back of pins.
Same as configuration above, except added nylon-coated tensile member (3/64-in. OD with 110-lb tensile strength) terminated to modified strain relief backshell via a swivel	141.0	Tensile member broke at looped connection to swivel; wires pulled out on break at pins.
Same as first configuration, except added tensile member (3/64-in. OD with 110-lb tensile strength) terminated to Qwik-Ty backshell via swaged loop	150.0	Tensile member broke inside bundle, not at termination, and wires pulled out or broke at pins.

[a]Basic AWG 30 wire per symbol B, table 2.

Jacketing Material Abrasion

Although three protective jacketing materials were used in building the final harness assemblies, namely: Nomex braid, Kynar shrinkable tubing, and FEP 10-mil convoluted tubing, only Nomex and Kynar were scrape abrasion tested. This limitation was due to the inapplicability of the test method to the convoluted tubing. Table 18 lists the test results.

D

TABLE 18.–ABRASION TEST DATA

Jacketing material	Abrasion cycles to failure	Test conditions
Nomex braid, 32 carriers, 1200 denier	8616	Jacket material over a metal tube with OD equal to 55-wire bundle OD; other conditions per wire abrasion test
Kynar shrinkable tubing (12-mil recovered wall thickness)	727	

Weight Comparison of Jacketing Materials

The following comparison was performed by jacketing a 55-wire bundle of AWG 30 with the three types of material under consideration and a 24.0-in. length measured and weighed in each case with an electronic balance.

Table 19 gives the weight on a lb/1000 ft basis.

For reference purposes a 55-wire bundle of AWG 30 with 6-mil polyalkene insulation and without jacketing weighs 33.15 lb/1000 ft, and with Nomex braid and a tensile strain relief member it weighs 43.76 lb/1000 ft. In comparison, a 55-wire bundle of AWG 24 with 10-mil polyalkene insulation weighs 111.10 lb/1000 ft. The weight differential is 67.34 lb/1000 ft of 55-wire bundle.

TABLE 19.–JACKETING MATERIAL WEIGHTS

Jacketing material	Material weight, lb/1000 ft (over 55-wire bundle)
Nomex braid– 32 carriers, 1200 denier	9.160
Kynar shrinkable tubing	9.711
Convoluted tubing (0.010 in. wall and nominal ID 9/32 in.)	15.00

DESIGN EVALUATION

Small-gage wire design evaluation was conducted on a comparative basis and divided into three categories—wire, bundle, and system harness evaluations—as was done for the testing. The baseline for each of the evaluations was AWG 24 wire per MIL-W-81044/19.

WIRE EVALUATION

Based on an analysis of wire test data and the wire selection study as outlined in the previous section, two wire constructions emerge as the most effective combination of conductor and insulation with overall system performance. These are:

- *Construction I.* AWG 30 with 7 by 38 conductor, having one stainless steel strand as a core and 6 by 38 strands of high-strength, silver-plated copper alloy and 6 mils of cross-linked polyalkene insulation.

- *Construction II.* AWG 30 with 7 by 38 stranding of high-strength, silver-plated copper alloy with 5 mils of polyimide insulation to 616 tape construction (1/2 mil FEP, 1 mil Kapton, 1/2 mil FEP) 66% overlap.

Break Strength

Construction II meets the design goal of 10 lb break strength as indicated by the average test value of 10.9 lb. Construction I closely approaches the design goal, with an average test value of 9.3 lb. The impact of a stainless steel (S/S) strand on tensile strength was minimal in spite of the higher break strength of the S/S (1.8 lb) as compared to copper strand (0.7 lb). An increase of 0.1 lb break strength was obtained from construction I with one S/S strand (9.3 lb) as compared to construction II with no S/S strand (9.2 lb). This is due mainly to the higher percent elongation of stainless steel.

Flexure Characteristics

Flexure life, on the other hand, is improved significantly by inclusion of the S/S strand with construction I (774 cycles), comparing favorably to the AWG 24 baseline (915 cycles) when flexed at the center of a wire segment. In general, experience has shown that at the connector termination, the flexure durability of the contact crimp/wire transition is a cause for concern.

With the special modified 22D size contact and a heat-shrinkable identification and strain relief sleeve, the flexure life test went from 562 to 25 000 cycles without failure.

Abrasion Resistance

Abrasion resistance test data confirm that some form of jacketing is required to raise the abrasion resistance of the 6-mil polyalkene insulation from 34 (average) abrasion cycles to be equivalent to the 285 (average) abrasion cycles of the baseline AWG 24 MIL-W-81044/19 wire. Abrasion-resistant jacketing can be fabricated to meet any desired level of abrasion and will be included in the system evaluation.

Weight

Constructions I and II were almost of equal weight (0.53 lb/1000 ft) and constituted a considerable weight savings when compared to the baseline wire AWG 24 (2.02 lb/1000 ft). Note that use of stainless steel stranding does *not* carry a weight penalty. (Specific gravity for annealed copper is 8.97 gm/cu cm and for stainless steel 7.94 gm/cu cm).

BUNDLE EVALUATION

Evaluation of an open SGW bundle design without the benefit of protective jacketing or a strain relief member gives a baseline for evaluating the SGW harness assembly.

Flexure Strength

Test data on flexing 55-wire bundles near the terminal connector without any backshell support showed that both constructions I and II survived 50 000 cycles of severe dynamic flexing without any wire failure.

Tensile Strength

The two constructions were of approximately equal tensile strength. A 55-wire bundle of construction I broke at an average of 510 lb and a similar bundle of construction II broke at an average of 520 lb, a small increase. In both cases all wires broke simultaneously, showing excellent load sharing.

HARNESS DESIGN EVALUATION

Harnesses with a 55-wire main bundle and two branch circuits of 22 wires and 33 wires were fabricated. A description of the hardware and photographic records of the harnesses evaluated are given in the "SGW Harness System Concepts" section and figures 2 through 17.

Harness Tensile Strength

Two considerations are relevant: (1) the tensile strength of a wire run supported at nominal intervals (20 in. maximum) and (2) the tensile strength at the wire termination.

1) For the tensile strength of a wire run, the bundle strength criteria of 110 lb can be met by the insulated wires in runs of 12 AWG 30 wires. However, if special applications and installation situations demand a tensile strength greater than 110 lb, provision can be made to incorporate a tensile member in the wire bundle consisting of a stranded steel wire with an anti-abrasion covering (plastic jacket). Tensile members of 110 lb break strength were incorporated in the assemblies delivered to NASA-MSC.

2) At the terminations, the break strength is governed by the single-wire tensile strength, the contact crimp strength, the contact retention strength, and the wire bundle load sharing characteristics.

A tensile member terminated between the connector and structure provides a tensile capability which would ensure that the most vulnerable portion of the wire run is protected from inadvertent tensile stresses during harness installation and service. Figure 15 shows a tensile member attached to simulated structure. Harness tensile test data show that a tensile member in a 22-wire (AWG 30) bundle almost doubles the break strength of the harness. Standard connector backshell hardware can be designed to anchor one end of the tensile member, and the other end can be suitably fastened to structure via a swivel and cable clamp, as illustrated in figure 12.

In regard to a tensile member, the following conclusions can be drawn:

- Any level of tensile strength can be met.
- Tensile stress relief can be applied locally at the ends of the harness.
- Hardware for anchoring the stress relief wire is available.
- The tensile member does not degrade flexure life, abrasion resistance, and maintainability of the harness system.

Harness Flexure Strength

This was primarily a connector/wire/strain relief evaluation. Various stress and tensile termination techniques were compared to standard methods. The added flexure stiffness due to the harness jacketing improved the flexure life without a negative impact on installation, repair, and assembly.

Harnesses of various configurations were flexed in excess of 88 000 cycles without any failure. This exceeds by far any practical design requirement. The convoluted tubing developed a split but still provided protection. As an added flexure strain relief for the contact/wire transition, the modified contact was evaluated with and without shrinkable sleeve strain relief. With the sleeve, the wire was flexed 25 000 cycles without failure. Without the sleeve the wire broke at 284 cycles.

Note that a 22 size contact qualified to accept an AWG 30 wire is not available, although some manufacturers do process an AWG 30 wire in a 22 size contact.

Harness Abrasion Resistance

It was established that the abrasion requirement would be 285 scrape cycles, which is the abrasion capability of an AWG 24 (10-mil insulation) per MIL-W-81044/19 wire. Accordingly, the outer jacket of the harness plus the abrasion of the wire insulation should add up to 285 scrape cycles. To simplify the requirement an outer jacket abrasion requirement of 285 cycles was used.

To evaluate the ability to provide abrasion and cut-through protection over and above that provided by the thin-wall insulation of the SGW, the abrasion resistance of various outer jackets was tested. Test data show that Nomex braid is superior (8616 cycles) to Kynar tubing (727 cycles), although both materials exceeded the abrasion requirement (285 cycles). As stated earlier, convoluted tubing was not compatible with the test method used. However, it will offer the wire significant abrasion protection.

Harness Weight

Significant weight saving is realized due to thinner insulation, AWG 30 wire, and high-density connectors when comparing the jacketed harness to the conventional open harness with MIL-W-81044/19 AWG 24 wires.

Data obtained show the weight of AWG 30 to be one-fourth that of AWG 24 on a 1000-ft basis. Jacketing material and tensile members add a small weight penalty but provide SGW systems with better physical protection than conventional wire systems. Among the three jacketing materials evaluated, Nomex offers the best weight advantage, with Kynar shrinkable tubing presenting the second choice over convoluted tubing.

Based on the assumption of a vehicle using a total of 100 000 ft of wire, including 34 000 ft of signal wire, a total weight saving of 50 to 75 lb would be realized.

Backshell Hardware Evaluation

Several types of backshells were evaluated; these are illustrated in the section "SGW Harness System Concepts."

Standard MS27211 Cable Clamp With Tensile Anchor

This off-the-shelf item is used extensively and can be adopted to anchor a stress relief wire as shown in figure 12. The following process control must be exercised.

- Bundle diameter must be built up with tape to obtain proper strain relief on this bundle and to ensure that the bundle is not pulled to one side, creating stress on the wire and grommet holes.

- The necessity to fasten the MS27291 cable clamp to the bracket arms with threaded hardware is a potential damage hazard. Screw driver slip could damage wire and insulation.

Qwik-Ty Cable Clamp (CTR01 X)

This is also standard off-the-shelf hardware that has been in use for some time. A tensile member with a loop formed at the end can be suitably anchored to the clamp. No tools are required to rework the bundle. To ensure good strain relief the wire bundle must be securely tied to the clamp, as illustrated in figure 10.

Shrinkable Boot

To provide more protection and a complete enclosure to the termination, a shrinkable boot over either the standard MS27211 or the Qwik-Ty cable clamp is practical and was included in harness assembly hardware for evaluation. The boot adds a weight penalty and, once installed, restricts access to the back of the connector for maintenance. For this function the boot must be cut and stripped (fig. 11). This operation requires careful handling to prevent damage to the wires. Once cut a new boot must be used unless a zipper-type boot were applied.

"Conflex" Connector Adaptor

An adaptor allows the conflex convoluted tubing to be attached to the connector (fig. 8). It can also be adapted to terminate a braided jacket to the connector. The adaptor completely shrouds and protects the wire terminations. It allows easy rework by unscrewing the adaptor and retracting the convoluted tubing. One disadvantage is the weight, which compares unfavorably with either of the cable clamps.

Braid/Convoluted Tube Transition

This unique transition device proves the capability of using convoluted tubing on braided harnesses to gain connector access and offers a structural tiedown feature when transitioning from braid to convoluted tubing. Figures 13 and 14 illustrate the use of this device.

CONCLUSIONS

On the basis of the results of this study, it is concluded that the use of SGW systems will result in significant weight and space benefits as compared to standard baseline round wire. These benefits can be achieved while maintaining adequate design integrity. Specific conclusions as to each element of SGW are listed below.

SGW

From the results of the tests conducted the following conclusions can be drawn:

- The use of SGW in sizes down to AWG 30 is feasible with existing hardware.
- SGW with stainless steel stranding provided significant wire flexure improvement but minimal tensile advantage.
- The use of a shrinkable sleeve with modified contacts for support of the wire terminations is recommended.
- SGW bundles should be applied in jacketed, multiconductor cable form.
- Limited additional training is required.
- SGW has a significant weight advantage as compared with the baseline AWG 24 round wire.

CONNECTORS AND ACCESSORIES

- Use of standard circular connectors is acceptable with SGW.
- Limited additional training in terminations and handling is recommended.
- Standard backshell hardware can be used in harness assemblies.

SGW HARNESS SYSTEM

- Harness tensile derating (ratio of application to design strength) shall be limited to 50% maximum.

- Design practice for SGW harnesses should limit applications to a minimum of 12 AWG 30 wires.

- At the harness ends a tensile strain relief is desirable. This tensile wire can be terminated at the connector backshell hardware and the other end, at approximately the first bundle clamp position, tied down to structure.

- The tensile strain wire should be covered with a flame-retardant plastic jacket to prevent abrasion of wire insulation.

SGW HARNESS DESIGNS

- A recommended SGW harness design is shown in figure 25 for use where "in-place" maintenance of the harness terminations is not a normal occurrence.

- In applications requiring "in-place" maintenance, the SGW harness jacket should transition to convoluted tubing at the ends (fig. 26).

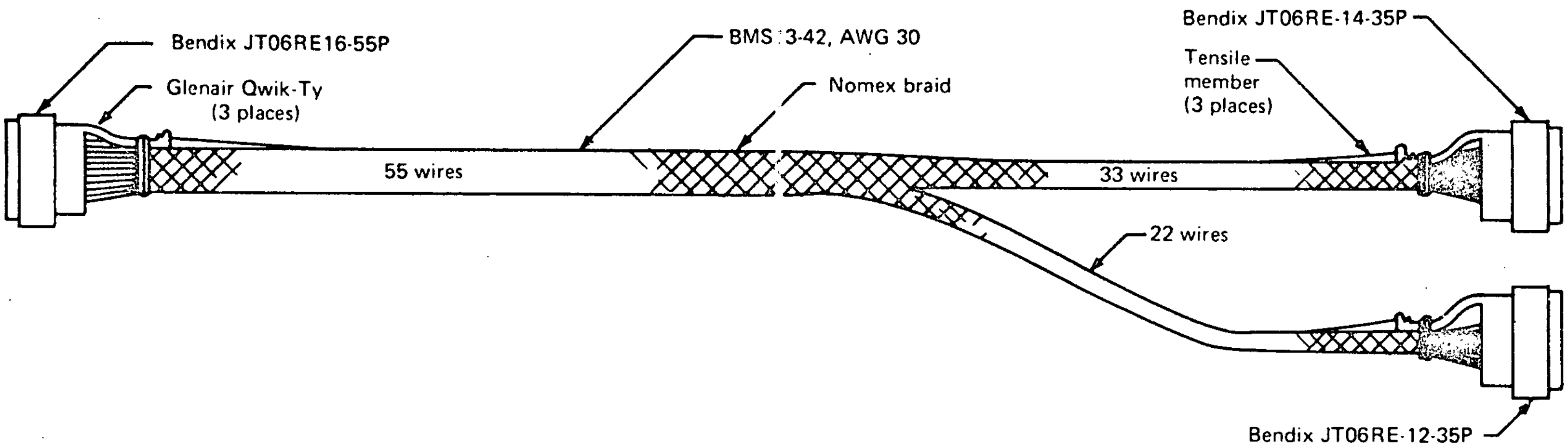


FIGURE 25.—SGW HARNESS—TYPE I

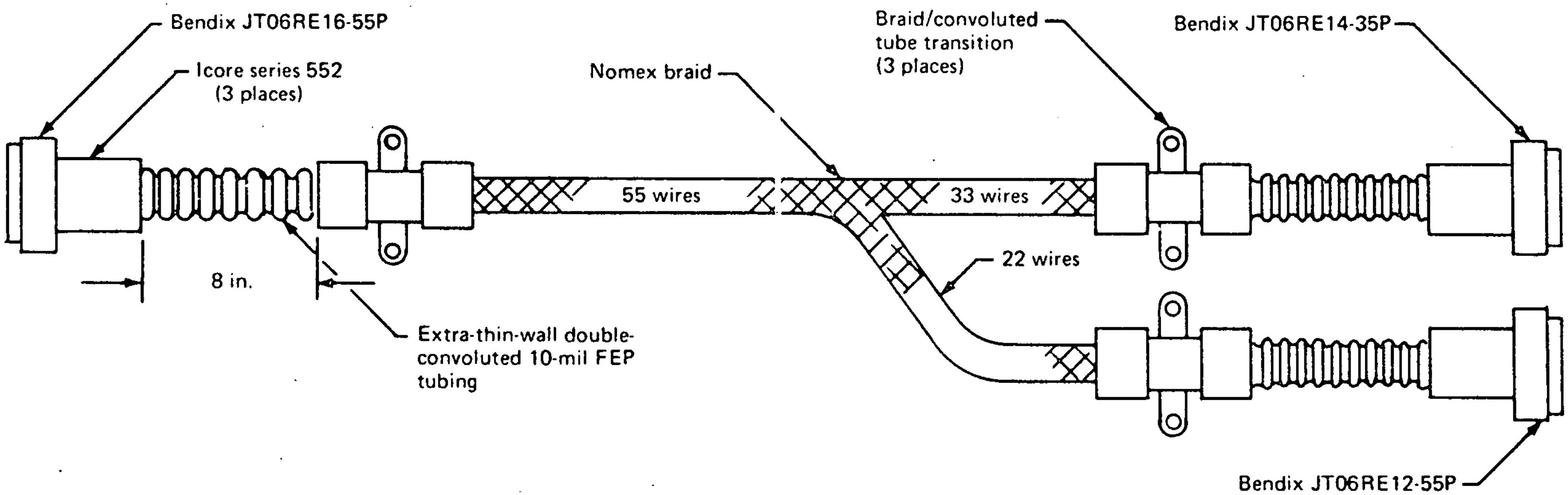


FIGURE 26.—SGW HARNESS—TYPE II

RECOMMENDATIONS FOR FOLLOW-ON STUDY

The SGW study showed the feasibility of methods and application of stress relief and mechanical protection which can be adopted to ensure system reliability. Further developments in the following areas are recommended.

SGW CONTACT DEVELOPMENT

A requirement exists for 22 size contacts to properly accommodate AWG 30 wire. The work done under this contract proved the feasibility of modifying the 22D size contact with a smaller crimp barrel to suit an AWG 30 wire and further modifying the contact to accept a shrinkable sleeve for strain relief.

It is recommended that a program be initiated to investigate the development of contacts for SGW application. This program would include:

- Contact design
    - Crimp evaluation
    - Crimp-through wire insulation concepts
- Sealing grommet design

SGW DEVELOPMENT

The wire test data analysis conducted in this program included a single composite construction of six strands of HSA and one strand of stainless steel. An expansion of this study to include a higher number of tensile stress strands is recommended. The study should determine:

- The practical number of tensile relief strands and their stress/strain characteristics relative to HSA strands.
- The effect of tensile relief strands on terminations–soldered, welded, or crimped.

- The effect of thermal cycling on termination integrity with one, two, or more tensile relief stands.

- Application of copper-clad steel strands to SGW.

SGW HARNESS SYSTEMS

This study generated data on general applications of harness systems in pressurized areas. It is recommended that further development studies be conducted to produce specific requirements and harness recommendations for both pressurized and unpressurized areas. These studies would be directed to provide data over a range of applications.

The program should define specifically the environmental, mechanical, and electrical requirements of each type of wire harness and provide a recommendation to meet each particular application.

SGW SAFETY, RELIABILITY, AND LIFE EVALUATION

Electrical wire bundles have not been subjected to the same degree of reliability analyses, design control, and maintenance actions as airframe control cables and electronic equipment. However, a considerable amount of failure mode data is available throughout aerospace companies, the airlines and the military, and it is believed that a program to collect and assemble these data in a form usable by the designer should be carried out. A detailed rationale for this program is given in the following paragraphs. The objectives of the program would be to:

a) Establish techniques and methods for determining service life for SGW systems wiring and document the results in a study report recommending a method for service life analysis.

b) Establish a program to track and obtain data that will result in wiring stress and fatigue life standards suitable for a future design manual for SGW systems wiring.

c) Obtain existing data bank failure rate and mode information for aircraft wiring. Use these data to develop curves and work out specific results by application of the methods established in (a) above. This will be accomplished by performing the following:

    1) Survey the industry and tabulate failure mode data (e.g., Boeing Commercial Airplane Group customer service and Boeing military service access to U.S. Air Force data, etc.).

2) Analyse these data to develop failure distribution curves.

d) Submit a document to include program work (data acquisition, data analysis, reliability analysis technique) and make recommendations for continued activity.

In practice, certain sections of aircraft wiring, such as those connected to frequently replaced units or in unprotected "traffic" areas, receive heavy wear while other sections may remain undisturbed for the life of the aircraft. Ideally, the designer should have sufficient data on wiring to enable him to design bundles that provide adequate reliability and safety for the least installation and maintenance cost. To achieve this objective, data similar to those generated for resistors shown in figure 27 are required for wire bundles.

However, in spite of the fact that much effort is spent recording failures on military and civil aircraft, there are still no data available to the designer, as is shown in tables 20, 21, and 22 taken from MIL-HDBK-217A.

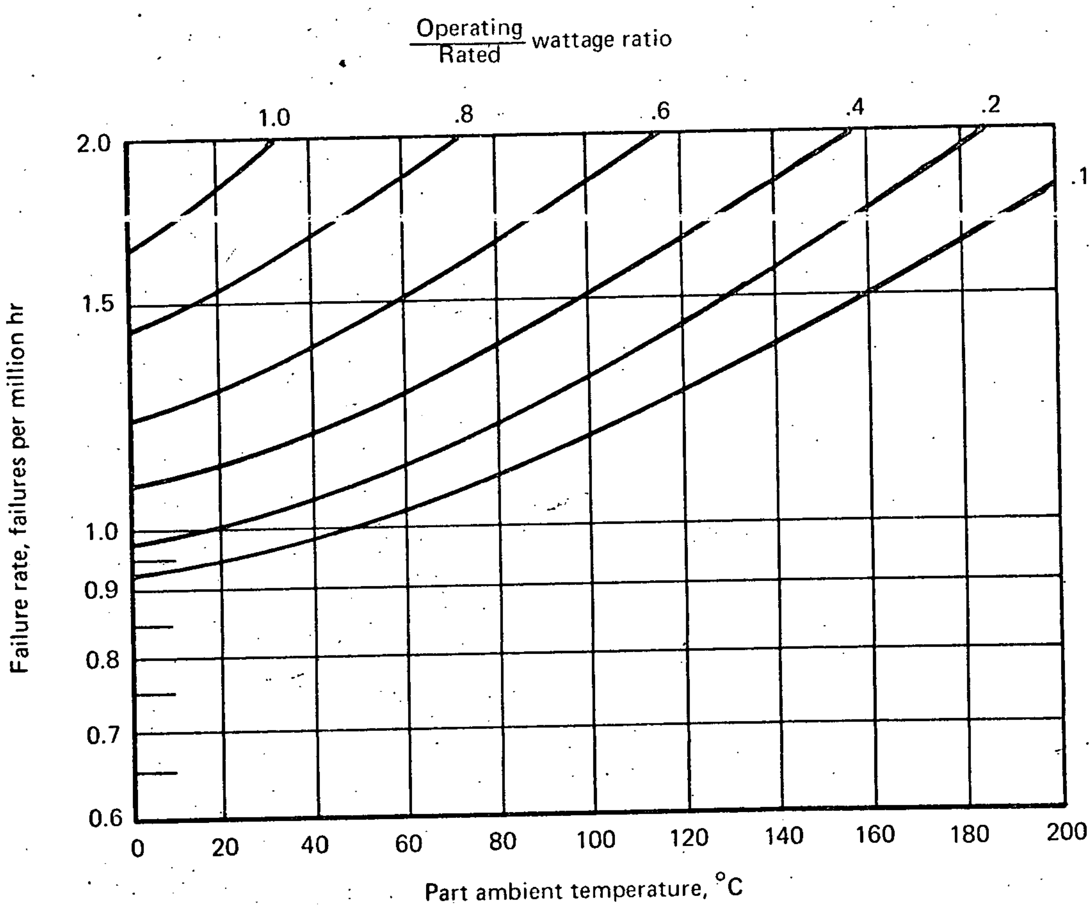


FIGURE 27.—TYPICAL FAILURE DATA

TABLE 20.—WIRING FAILURE DATA[a]

Type termination	Ground	Vehicle-mounted ground	Shipboard	Airborne	Missile
Wire	No data	No data	No data	No data	No data
Solder connection	0.0057	0.034	No data	0.034	No data
Resistance weld connection	0.0019	0.079	No data	0.079	No data
Wire wrap	0.0000037	No data	No data	No data	No data
Crimp	0.016	No data	No data	No data	No data

[a]Failure rates are shown in failures per 10^6 hr.

TABLE 21.—APPLICATION K-FACTORS FOR PRINTED WIRING USE

Ground	Vehicle-mounted ground	Shipboard	Airborne	Missile
No data	No data	No data	No data	No data

TABLE 22.—APPLICATION K-FACTORS FOR CABLE USE

Cable type	Ground	Vehicle-mounted ground	Shipboard	Airborne	Missile
Coaxial	No data	No data	No data	No data	No data
General	No data	No data	No data	No data	No data

The absence of quantitative data in sources such as MIL-HDBK-217A and RADC-TR-67-108 is not without reason; namely, that the raw data available from both the military and commercial failure recording systems is in neither the detail nor the order to permit the analysis required to fill in the above blanks. This assertion is based on an extensive analysis undertaken by Boeing in 1966 on the reliability of wiring and connectors used on the model 727. The 1966 analysis produced data such as is shown in table 23, and, while the analysis served to identify problem areas, it did not provide data of the kind required to ensure adequate wiring reliability for small-gage wire systems. The 1966 study covered 2547 x 10^6 wire segment flight-hours.

TABLE 23.–ABSTRACT FROM BOEING WIRING FAILURE STUDY

Characteristic	Defects		
	Along-wire segment	At connectors	Total
Bad splicing	2	–	2
Clamping faults	3	–	3
Chafing or worn cable	10	–	10
Bare wire and insulation deterioration	6	1	7
Broken	109	80	189
Shorted	17	1	18
Burned	4	–	4
Shield crimping faults	–	1	1
Faulty connections	–	1	1
Moisture	1	–	1
Kinked conduit	8	–	8
Production errors (incorrect wire, etc.)	30	19	49
Inadequate installation (short lengths, etc.)	5	–	5
Loose	40	3	43
Open	5	3	8
Missing	4	–	4
Unknown	85	25	110
Total	329	134	463

The work required to ensure adequate wire reliability for SGW systems requires the scientific application of suitable design data, adequate control of quality during manufacture, and proper uses in service. To provide a scientific basis for design, the following are proposed:

- Evaluate and detail a more comprehensive program of data collection and analysis, by applying the techniques for analysis of data and those for reliability prediction for equipment with a high mean time between failures. This process will consist of the choice of suitable parametric or nonparametric statistics that describe with sufficient accuracy the random and nonrandom failure characteristics of wires and wire bundle hardware.

- Plan a program capable of tracking and obtaining the necessary data to provide wiring stress and fatigue life data suitable for use in a future design guide for SGW systems. This requires study of failure physics based on a systematic set of tests and analyses of field failures to establish the characteristics of the materials, processes, and assembly techniques used. Mathematical techniques such as the statistical design of experiments will be used where required.

From the above discussion it is evident that a rigorous service-life study of SGW system wiring is in order. It is imperative that service life analyses, with supporting data, be developed. This would then raise design confidence in wiring compatible with that already developed in other key technologies such as structures, solid-state components, and closed-loop control systems.

APPENDIX

TEST PLAN AND EVALUATION REQUIREMENTS FOR SMALL-GAGE-WIRE UTILIZATION

PURPOSE

The purpose of this plan is to evaluate the ability of small-gage wire and wire bundles to survive the environments encountered in production, installation, and in-service use on air and space vehicles.

SCOPE

This plan includes test methods, conditions, limitations, a list of equipment, and test parameters required for performing evaluation testing.

REFERENCES

D6-13046	*Electrical and Electronic Wiring Design Methods and Practices*
MIL-STD-202D	*Test Methods for Electronic and Electrical Component Parts*
MIL-C-38999	*Connector, Electrical, Circular, Miniature, High Density, Quick Disconnect*
MIL-C-81511	*Connector, Electric, Circular, High Density, Quick Disconnect, Environmental Resisting*
MIL-W-81044	*Wire, Electric, Crosslinked Polyalkene, Insulated, Copper*
MIL-T-5438	*Tester, Abrasion, Electrical Cable*
MIL-STD-810A	*Environmental Test Methods*
Federal Test Method Standard No. 228,	*Cable and Wire, Insulated, Methods of Testing*

RESPONSIBILITIES

The Electrical Technology group of The Boeing Company will be responsible for testing and documentation of test details and results.

PROCEDURES

Test Equipment

The test equipment used in this program will have been certified and calibrated within 90 days prior to performing all specified tests. A list of the equipment to be used is included with the description of each test.

Test Conditions and General Environments

Unless otherwise specified, tests shall be conducted at room ambient pressure, temperature, and relative humidity per MIL-STD-202, "General Conditions."

Sample Description and Preparation

Test samples for complete small-gage wire evaluation are divided into three categories: wire samples, bundle samples, and harness samples, as described below:

- *Wire Samples*—The wire samples shall be 20 in. long. Fifteen samples of each of the wire constructions listed in table A-1 shall be tested per the sequence indicated in table A-2.

- *Bundle Samples*—The bundle samples shall be 20 in. long and consist of 55 wires—six bundles of each wire construction shall be prepared and tested as shown in table A-3.

- *Harness Samples*—Five harnesses shall be made up of 55 wires each with an ASTRO 348 connector (MIL-C-81511) on one end and two JTRE connectors (MIL-C-38999) on the two branches of the other end. Tensile members of nylon-coated stainless steel run alongside the wires and jacketed in Nomex braiding, heat-shrinkable tubing, or convoluted tubing will be included and evaluated. Harness testing shall follow the sequence of table A-4.

Test Sequence

The tests listed in tables A-2, A-3, and A-4 have been selected to evaluate the small-gage wires, bundles and harnesses. These tests, performed in the sequence shown, will provide the required data with a minimum of test time and cost.

TABLE A1.–SMALL GAGE WIRE CONSTRUCTION

AWG	Conductor	Insulation	Supplier	Applicable military specification
30	6x38 silver-plated high-strength copper alloy 135 and 1x38 stainless steel 304	6-mil crosslinked polyalkene	Raychem	–
30	7x38 silver-plated high-strength copper alloy 135	6-mil crosslinked polyalkene	Raychem	MIL-W-81044/13
30	7x38 silver-plated high-strength copper alloy 135	5-mil polyimide–616 tape (1/2-mil FEP, 1-mil Kapton, 1/2-mil FEP), 66% overlap	Haveg	–
30	7x38 silver-plated high-strength copper alloy 135	10-mil type-E Teflon (ribbon)	Gore	MIL-W-16878/4A
30	7x38 silver-plated high-strength copper alloy 135	5-mil type-ET Teflon (ribbon)	Gore	MIL-W-16878/6A
25	Flat conductor unplated copper	4-mil-wall FEP + H-film each side	Hughes	MIL-W-55543
24	19x36 silver-plated high-strength copper alloy	10-mil crosslinked polyalkene	Raychem	MIL-W-81044/19

TABLE A2.–WIRE TEST SEQUENCE

Wire test	Wire sample No.														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Insulation	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Tensile	x	x	x	x	x										
Flexure						x	x	x	x	x					
Abrasion											x	x	x	x	x

TABLE A3.—BUNDLE TEST SEQUENCE

Bundle test	Bundle sample									
	1	2	3	4	5	6	7	8	9	10
Insulation resistance	x	x	x	x	x	x	x	x	x	x
Flexure	x	x	x	x						
Insulation resistance	x	x	x	x						
Flexure to failure	x									
Tensile (use MIL-C-26500 connector)				x	x	x	x	x	x	x

TABLE A4.—HARNESS TEST SEQUENCE

Harness test	Harness sample				
	1	2	3	4	5
Insulation resistance	x	x	x	x	x
Flexure		x		x	x
Insulation resistance		x		x	x
Vibration			x	x	x
Insulation resistance			x	x	x
Abrasion	x	x		x	

Test Sample Coding

A four-digit number will be used, as shown in the following example:

WB 1-3

- 3 — Sample number (1-15)
- 1 — Number of wires in sample (1 = single wire; 55 = complete bundle)
- B — Supplier
  - A Raychem
  - B DuPont/Haveg
  - C Gore
  - D Hughes
  - E Boeing Materiel
- W — Sample configuration (W = wire, B = bundle, H* = harness)

Test Methods

Tensile

Objectives.—The objectives of this test are to:

- Determine the ultimate tensile strength of small-gage wires and wire bundles with special construction features to increase the tensile strength.
- Determine, from the individual wire strength, the minimum number of wires that must be harnessed together to provide a design margin comparable to present acceptable designs.
- Evaluate wire/contact crimp tensile strength.

Equipment.—An Instron tensile tester with temperature chamber and grips designed to produce uniformly distributed axial tension in the sample, will be used. A discontinuity monitoring system will also be provided for this test.

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*Each final harness configuration will be sketched and components clearly identified.

Procedure.—The test shall be performed in accordance with FTMS 228 method 3212, except as follows:

- Instron crosshead travel speed shall be 1.0 in./min
- Elongation shall not be considered for wire bundle tests as this will vary considerably between wire bundles using the same construction but with different configurations
- Sample lengths shall be as defined in "Sample Description and Preparation"
- The tensile strength of the wire shall be the arithmetic average of the results obtained over the specimens tested.

Requirements.—The minimum acceptable tensile strength for a small-gage wire bundle shall be 110 lb. This number is based on a minimum of three wires of AWG 24 high-strength copper alloy per MIL-W-81044/19. Failure of insulation, termination, or tensile member of a harness assembly to meet this requirement will constitute a harness failure.

Insulation Resistance

Procedure.—The insulation resistance shall be measured with a megohmmeter (1% FS accuracy) as follows:

- The insulation resistance shall be measured at 500 Vdc and the reading allowed to stabilize for 1 minute.
- Single wires shall be tested between the conductor and salt solution (5% NaCl) in which they are immersed.
- Specimens shall remain immersed for 4 hr before testing.
- Bundle insulation resistance shall be tested between a single conductor and all other conductors arranged in two or more groups.

Requirement.—Insulation resistance shall be greater than 5000 megohms for 1000 ft.

Flexure Test

Objective.—The objective of this test is to evaluate the effects of flexing on the proposed wires and wire bundle construction, especially near the termination area. Results will be compared to determine the effects of stress relief members, tensile members, and other aids on the flexure life of the bundle.

Equipment.—The test will be conducted on a Boeing-designed and fabricated pneumatic flexer adjustable to flex angles of 0° to 180° with mandrels of various diameters as required by the test. In addition, a discontinuity monitoring circuit capable of detecting discontinuities of 1μsec or greater will be a part of this setup.

Procedure.—The test samples shall be bent repeatedly in alternating directions through a bend angle of 90° on each side of the vertical centerline of the mandrel at a rate of 30 cycles/minute for 100 cycles. Mandrel diameter shall be three times the sample outside diameter.

Requirements.—Samples shall endure 100 cycles of flexing with no evidence of damage. Failure of any single wire, insulation, or termination shall constitute a harness failure. Also, a discontinuity of .1μsec or greater shall constitute a failure.

Vibration

Objective.—This test is intended to simulate the type of vibration experienced by spacecraft wiring in order to evaluate the vibration characteristics of the various bundle configurations.

Equipment.—A vibration system with control and programming equipment for sinusoidal sweep and random vibration tests will be used in addition to a discontinuity detecting system for monitoring any discontinuity of 1μsec or greater.

Procedure.—All contacts shall be wired in a series circuit, and 100 mA of current shall be allowed to flow through the series circuit during vibration. The bundles shall be mounted side by side on the vibration fixture by cable and harness mounting hardware. Bundles shall be clamped to nonvibrating points at least 8 in. from the rear of the connector. The vibration envelope shall be per MIL-STD 810A, method 514.1, class 1, curve E.

Requirement.—There shall be no current discontinuities of 1μsec or greater, no disengagement of contacts, and no breaking of wires or tensile members.

Scrape Abrasion Resistance Test

Objective.—This test is proposed to evaluate the abrasive action of a sharp, hard surface on the physical protection of a wire and a wire bundle.

Equipment.—The scrape abrasion tester shall consist of a weighted scraping fixture which abrades the surface of the wire insulation by scraping in both directions along the longitudinal axis of the wire for a distance of no less than 2 in. and at a speed of 30 to 60 cycles/min. The scraping device that contacts the wire surface shall be a hardened steel blade as shown in figure A-1. During the scraping action, the vertical axis of the blade shall be maintained at 90°± 2° to the centerline of the test specimen. The test specimen shall be held taut and straight by clamps on a flat supporting anvil. The device shall be equipped with an electrical circuit designed so that when the scraping blade abrades through the protective surface the machine will stop.

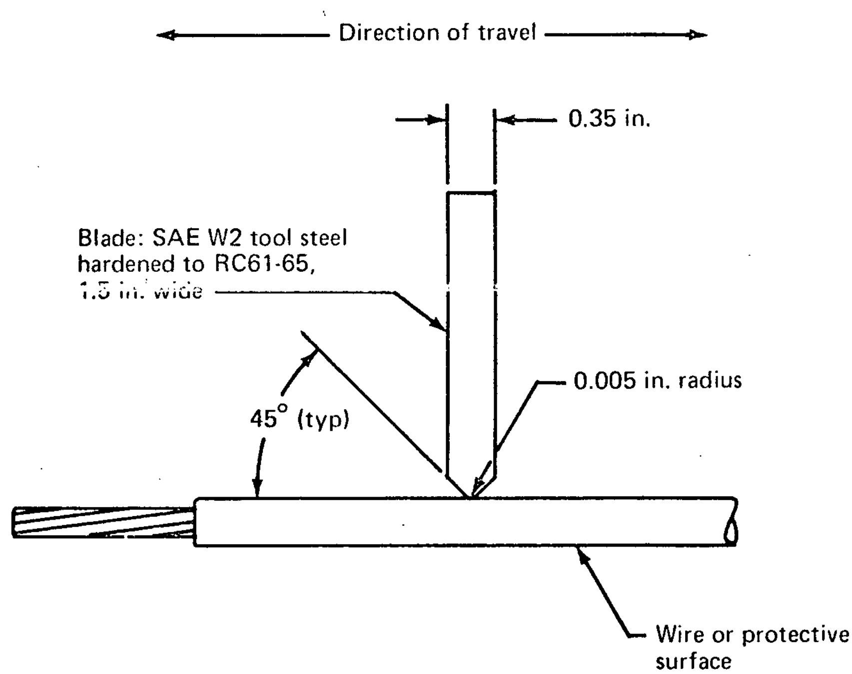

FIGURE A-1.—SCRAPE ABRASION TOOLING

Procedure.—The test specimen shall be clamped in the tester and subjected to the abrasion test using a weight to be determined by empirical methods consistent with meaningful comparative results. Four tests shall be performed on the specimen with the specimen being moved forward 4 in. and rotated 90° between each test.

Requirement.—The scrape abrasion failure rate shall be the number of cycles required for the scraping blade to abrade through the protective surface and stop the machine.

Wire Weight

Purpose.—A test will be conducted to determine the weight of the finished insulated wire.

Specimen.—One specimen 2 ft long will be used.

Equipment.—This will consist of a steel scale (1/64 in. or finer) and a balance of 0.20 gm accuracy.

Procedure.—The test will be performed as follows:

1) Cut specimen ends squarely.

2) Measure length to nearest 1/64 in. and record as "L."

3) Weigh to within 0.20 gm and record as "W."

4) Remove insulation and free conductor from any material. Weigh and record as "W_1"

   (a) The weight of 1000 ft of the insulation will be calculated as follows:

   $$\text{lb/1000 ft} = \frac{W - W_1}{L} \times 26.455$$

   (b) The weight of 1000 ft of conductor will be calculated as follows:

   $$\text{lb/1000 ft} = \frac{W_1}{L} \times 26.455$$

   (c) The weight of finished insulated cable (wire) will therefore be:

   lb/1000 ft = weight of insulation (a) + weight of conductor (b)